AIEE SOUTHERN DISTRICT MEETING, ROANOKE, VA., NOVEMBER 16-18, 1943

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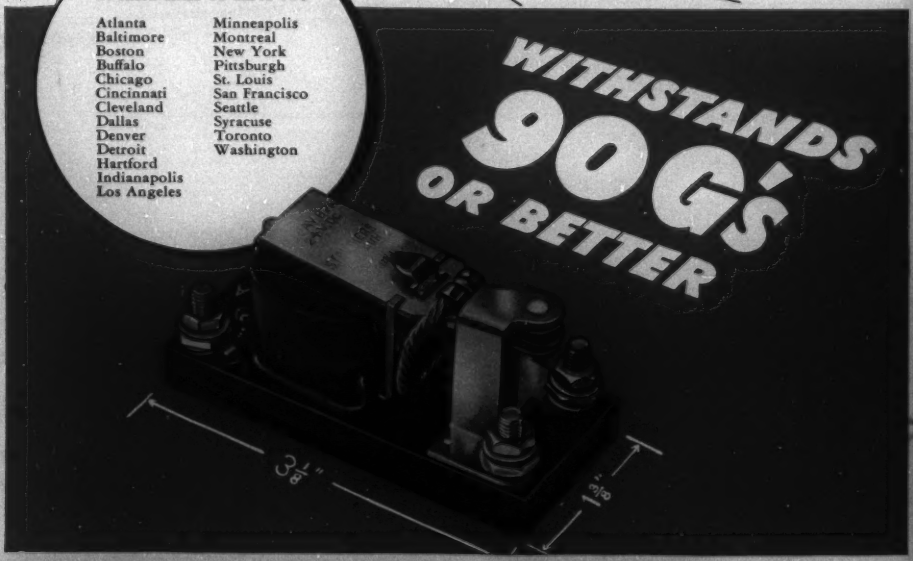

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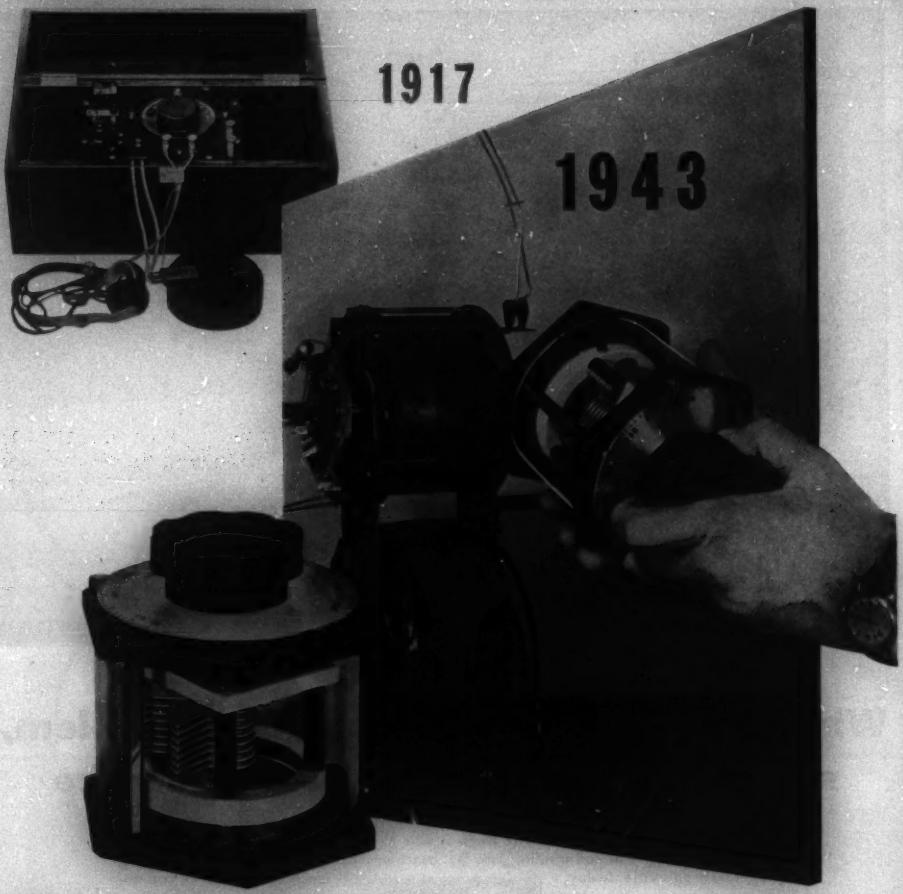

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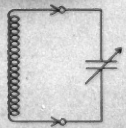

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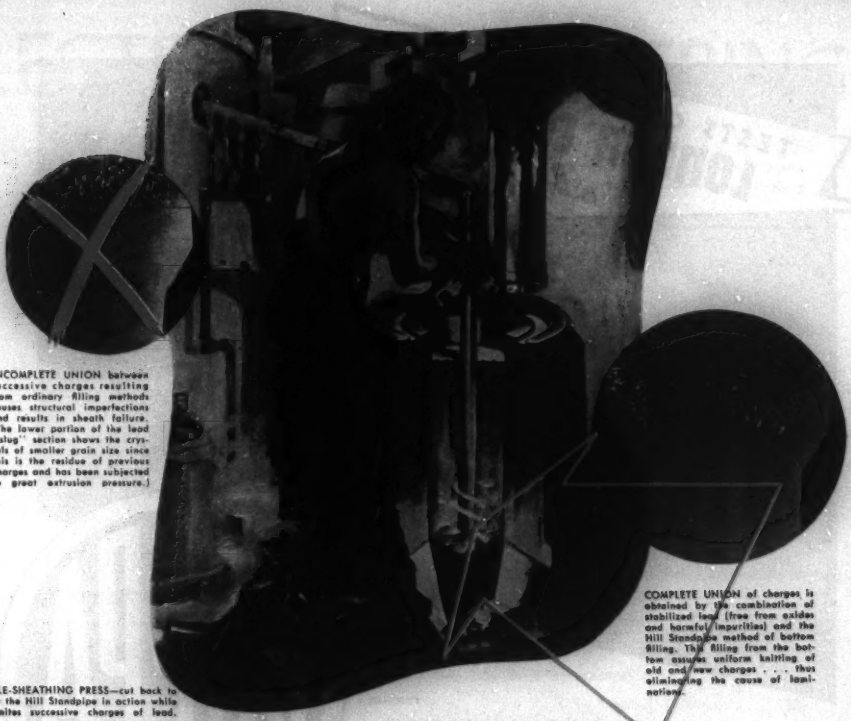

INCOMPLETE UNION between successive charges resulting from ordinary filling methods causes structural imperfections and results in sheath failure. (The lower portion of the lead "slug" section shows the crystals of smaller grain size since this is the residue of previous charges and has been subjected to great extrusion pressure.)

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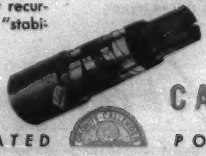

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ELECTRICAL ENGINEERING

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NOVEMBER
1943

The Cover: Interior of the generator room at Claytor Dam, Appalachian Electric Power Company, near Roanoke, Va., where the AIEE Southern District will hold a technical meeting November 16–18. Rating of each of the four units is 18,750 kva.

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The heavier oxygen ions follow a straighter path than the lighter nitrogen ions and are directed through a tiny exit slit onto a plate where they give up their electrical charge. The amount of this charge, amplified and recorded by sensitive electrical instruments, is an extremely accurate measure of the *quantity of oxygen* in the gas mixture.

The starting voltage is then changed to allow the nitrogen ions to pass through the same exit slit—thus measuring the *quantity of nitrogen*. This same principle applies to the analysis of complex hydrocarbon mixtures.

The development of the mass spectrometer . . . for the quick, accurate analysis of butadiene . . . is a typical example of the way Westinghouse "know how" in electronics is tackling the wartime problems of industry in an effort to speed victory.

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Copper Mining and the Utah Copper Mine

ROBERT S. LEWIS

COPPER, without much question, was the first metal smelted by man. Used as the native metal, or else alloyed with tin to form bronze or with zinc to form brass, copper was known and utilized many thousand of years before Christ; in fact the Egyptians, before 6000 B.C., fashioned copper into sheets, knives, and harpoons. Egyptian paintings of 1500 B.C. illustrate the smelting of copper in primitive furnaces. The Romans obtained copper from the island of Cyprus in the Mediterranean Sea and called the metal "aes cyprium," a term which became transformed into "cuprum" from which the word copper is derived. A bronze head of Brutus, an example of the sculpture of the Republican period dated about the 4th century B.C., is a magnificent piece of work.

In the Western Hemisphere copper was mined in Chile before Pizarro conquered the Incas in 1533. However, the first Spanish mining was in 1601, and the first modern smelting in 1842. Copper was discovered in the United States in 1632, but the first mining of copper in this country was done in 1705 at the Simsbury mine in Connecticut. The Lake Superior copper region was opened in 1830. Copper mining at Ducktown, Tenn., began in 1843. Both the Butte, Mont., and the Bisbee, Ariz., districts were well known by 1874, and by 1905 the era of the large low-grade open-pit or "porphyry copper" mines began in the United States and in Chile. In 1924 sampling, by drilling, of the Northern Rhodesia copper region disclosed large deposits of unusually rich copper ores, some 150 miles to the southeast of the already known rich oxidized ores of the Katanga district in the Belgian Congo.

From early times up to 1880 copper was produced in relatively small amounts. From 1801 to 1810 the world's production of copper was but slightly over 18,000 tons, or less than one month's production of some of our present-day mines. England was the leading producer until 1850, when Chile assumed first place. In 1883 the United States became the world's leading copper producer, and it still holds that place, although its dominant position in the world's markets is steadily declining. Thus, from 1913 to 1929 the United States' production of copper rose 64 per cent, but that of all other countries increased 129 per cent.

Essential substance of a paper presented at the AIEE national technical meeting, Salt Lake City, Utah, September 2–4, 1943.

Robert S. Lewis is professor of mining, University of Utah, Salt Lake City, Utah.

The history of copper mining is of especial interest inasmuch as copper has become one of our most strategic weapons in the winning of the war. One of the principal methods in use today is open-pit mining. The mine of the Utah Copper Company described in this article is typical of modern open-pit mines.

In 1938 the world's mine and smelter production of copper was, in round numbers, 2,229,000 short tons distributed as follows:

United States	24.5 per cent	Russia	5 per cent
Chile	17 per cent	Japan	4.9 per cent
Canada	12.5 per cent	Germany	1.5 per cent
Rhodesia	12.4 per cent	Italy	0.05 per cent
Belgian Congo	6 per cent		

In several of these countries the production of copper has been greatly increased since 1938. In 1931 the British Empire produced 98,000 tons of copper and consumed about 170,000 tons. The rapid developments in mining in Canada and Northern Rhodesia increased copper production from 99,000 tons in 1925 to 685,000 tons in 1939. As a result of these developments, about 1,000,000 tons of copper were made available to the British Empire in 1940. Of this amount some 880,000 tons were shipped to England, but an unknown tonnage was sunk before it reached its destination. France, during the German invasion in June 1940, was able to reship some 83,000 tons of copper from Bordeaux to England, the United States, and French Morocco, but the Germans captured an estimated 80,000 tons at various ports, in addition to domestic stocks.

The world reserves, in short tons of metallic copper, were estimated by P. E. Barbour in the October 1934 issue of *The Engineering and Mining Journal* (see Table I).

From the standpoint of tonnage of ore, the Chuquicamata (Chile) mine of the Anaconda Copper Company leads with reserves of 1,035,000,000 tons of 2.15 per cent copper ore. The Potrerillos (Chile) mine, another Anaconda property, contains 124,000,000 tons of 1.47 per cent copper ore. The Braden Copper Company's mine in Chile contains 226,000,000 tons of 2.18 per cent copper ore. Contrast this low-grade ore with that from five Northern Rhodesia mines totaling about 500,000,000 tons of approximately 4.0 per cent copper ore. Some

Table I. World Reserves in Short Tons of Metallic Copper

Country	Tons	Per Cent
United States	20,993,000	21
Canada	5,620,000	5
Chile	35,499,000	34
Rhodesia	22,395,000	21
Belgian Congo	6,511,000	6
Russia	10,851,000	10
All others	2,961,000	3
Total	104,830,000	100

of these mines can produce ore for two or three years that will not fall below ten per cent copper. The rich Katanga belt, across from Rhodesia, has an estimated 40,000,000 to 80,000,000 tons of seven to eight per cent oxidized copper ore. Thus tonnage of ore alone is misleading unless the grade of ore is also stated.

In regard to Germany, Japan, and Italy, Germany produces normally about 33,000 tons of copper a year, mostly from her Mansfield mine, a bed of copper-bearing black shale only 15 inches thick and containing from two to three per cent copper. She has acquired by conquest the Bor mine in Yugoslavia that produced 64,200 tons of copper in 1938, and the Roros mine in Norway that produces about 20,000 tons of copper per year. Germany's consumption of copper averaged 237,000 tons a year for the period 1934 to 1938. During prewar years she accumulated large stocks of copper from abroad. In 1938 more than 85 per cent of her imports came from the Western Hemisphere and Africa, sources closed to her in 1940.

Japan's production of copper in 1938 was approximately 115,000 tons. Her imports in 1940 were about 146,000 tons, of which 109,600 tons came from the United States, 19,000 tons came from Chile, some 12,000 tons came from Canada, and 6,000 tons were from the Philippine Islands. A definite sign of the Axis' nations preparation for war was the growing imports of strategic minerals for several years before the beginning of hostilities. Thus Japan increased her imports of copper from 1,181 tons in 1930 to 146,000 tons in 1940. This unusual increase in imports of a strategic mineral was a clear warning of a coming war.

Italy's mines produced 335 tons of copper in 1935 and 1,000 tons in 1938, while her consumption of copper for those two years was 80,000 and 90,000 tons, respectively. The substitution of aluminum for copper in the electrical industry is expected to save about 20,000 tons of copper a year.

The United States is the only one of the world's largest consumers of copper that normally produces enough of the metal to satisfy its own requirements, thus making this country both the largest consumer and the largest producer of copper. In ordinary times the United States consumes about 80 per cent of the new copper it produces. As to the percentage distribution of copper production in the United States the figures are as follows:

Arizona	32 per cent	Nevada	9 per cent
Utah	27 per cent	New Mexico	8 per cent
Montana	14 per cent	Michigan	5 per cent

Other producing states 1 per cent or under

This figure will change a little as the Morenci mine in Arizona increases its output some 15 per cent.

Copper is characterized by its indestructibility under normal conditions of use. Hence, secondary or scrap copper is an important source of supply. In 1922 the tonnage of scrap copper thrown on the market was sufficient to bring on a closing of the primary copper producers for a period of ten months. From 1920 to 1923 more than 60 per cent of the copper sold was from scrap. In the depression of 1930 to 1935, when a strong effort was made by primary producers to curtail production, 80 per cent of our copper requirements was supplied by scrap. In this period the price of copper dropped to an all-time low of five cents per pound. This low price caused a tremendous increase in the use of copper in the building trades. In 1938 the production of secondary copper in the form of old and new scrap was about 360,000 tons or 65 per cent of the domestic-mine output.

Table II. Chief Uses of Copper in Industry

	Per Cent
Electrical manufactures	24.0
Manufacture for export	14.8
Wire and rods, but not power lines	12.0
Automobiles	10.3
Buildings	10.2
Total	71.3

Table III. Application of Copper to War Purposes

Item	Copper Required for Munitions
For every medium tank	998 pounds
For every 155-millimeter gun	2,839 pounds
For every *P*-40 plane	1,660 pounds
For every *P*-38 plane	2,982 pounds
For every *C*-62 cargo plane	2,850 pounds
For every battleship	2,000,000 pounds
For every scout car	150 pounds
For every 37-millimeter gun	600 pounds
For every 90-millimeter gun	1,480 pounds
For every 105-millimeter howitzer	250 pounds
For 0.30-caliber shells (per million)	13 tons
For 0.50-caliber shells (per million)	58 tons
For signal-corps wire	2,000,000 pounds per month
Total signal-corps requirements	10,000,000 pounds per month

In 1888 a Frenchman, M. Secretan, believing that the phenomenal development in the use of electricity has resulted in a demand for copper that had outstripped all capacity for production, attempted to corner the copper market. However, he miscalculated the stocks of copper in private hands and the amount of scrap that would be collected under the stimulus of high prices. He could not hold the price of copper up long enough to dispose of his huge stock at a good profit, and it took his bankers several years to market his accumulated mountain of copper.

As to the chief uses of copper in industry, they ordinarily rank as indicated in Table II. Some idea of the application of copper to war purposes may be gained from data in Table III.

If we examine the figures for the individual production per miner, using tons of ore per man-shift as the basis for comparison, we find a marked increase in the output of copper ore between early mining and recent mining, as shown by the data in Table IV.

The increase in output per man-shift is due to the development of improved methods of mining and the

Table IV. Output in Tons of Copper Ore Per Man-Shift

Copper industry as a whole	About 1/3 ton in 1880 and about 9 tons in 1936
For underground copper mining	About 2 tons in 1914 and 4 1/4 tons in 1936
For open-pit copper mining	About 9 tons in 1914 and 31 1/3 tons in 1936

use of better equipment and shows conclusively the advantage of open-pit mining, where this method can be used.

Though ores mined by open-pit methods are generally of lower grade than ores mined underground, the greater output per man-shift for open-pit mining results in a lower cost per pound of recoverable copper in the ore. Thus for the period 1926 to 1930 the direct mining cost only per pound of copper was 2.26 cents for open-pit mining as compared with 4.10 cents for underground block-caving methods (cheapest underground method of mining) and 4.53 cents for all underground mines.

Open-pit mining is applicable to ore bodies of large horizontal extent overlain by a capping or overburden that is not too thick, say not over 300 feet thick, although this figure varies at different mines. This capping has to be removed, and the ore is then mined in benches by power shovels. These benches vary from 25 to 50 feet in height and may be from 30 to 100 or more feet in width. They vary in number with the depth of ore, ranging from three or four to as many as 22 or even more. The benches should be so proportioned that the over-all slope of the pit is not steeper than the angle of repose of the material in the sides of the pit; else the sides would tend to slide into the pit, injuring men and equipment and delaying operations. Making the over-all slope of the pit sides much flatter than the angle of repose would insure safer operation, but the flatter the slope the greater is the yardage of overburden that eventually must be removed around the rim of the pit. Calculations are made to determine the maximum number of cubic yards of overburden that can be removed per ton of ore, and the pit slopes must be kept inside this limit if a profit is to be made from operations.

Overburden and ore must be drilled and blasted to proper size, so that the material can be handled by the power shovels. If some of the material breaks in pieces too large to be handled by the shovels, these pieces must be broken to proper size. This operation is called "secondary blasting."

Hauling ore and waste out of the mine is an important operation, and it sometimes presents a difficult problem. Millions of tons of waste or capping require a large volume of dumping space, which may be hard to find in mountainous country. The necessary long haul, in this case, may be a decided disadvantage in operations. In the pit, the railroad tracks may spiral around as they lead down to the bottom, but the grade must not be too steep. On a side hill, there must be switchbacks, preferably at each end of a level or bench, so that the trains can work their way up or down the slope.

In general, open-pit operations are affected adversely by bad weather, a heavy cost is incurred in equipping the mine, and a large capital outlay is required since much capping may have to be removed before any ore can be mined. To offset these disadvantages the large scale of operations results in a relatively low cost for labor. Operations are safer than in underground mining, and working outdoors makes for better health of workers. Flexibility of output is another important advantage, since production can be materially reduced, even to the point of shutting down, without incurring the high expense that closing an underground mine entails. Finally, the application of the flotation method of concentrating ores to the "porphyry coppers" makes it possible to secure a high recovery of the copper in these low-grade ores.

THE UTAH COPPER MINE

Location. The open-pit mine of the Utah Copper Company is situated about 30 miles southwest of Salt Lake City in the Oquirrh range of mountains. After the ore is mined, it is transported some 18 miles northward to the Magna and Arthur concentrating plants, where it is treated by the flotation process to yield molybdenum and copper concentrates. The molybdenum concentrates are shipped as a finished product, but the copper concentrates are smelted at the Garfield plant of the American Smelting and Refining Company, four miles west of the mills. The "blister copper" from the smelter, containing gold and silver and other impurities is shipped to the Baltimore refinery of the American Smelting and Refining Company, where the precious metals are recovered and the copper is converted into a purer marketable form.

History. Limitations of space do not permit presenting the interesting history of this mine in full, but the following brief chronology will give some idea of the length of time and the difficulties that were involved in promoting this first "porphyry-copper" mine, which was turned down by several engineers and financial interests, because no one had yet attempted to mine such a large deposit of such low-grade ore. In fact, some mining men said it could not be done successfully.

In July 1887, Colonel E. A. Wall visited the Bingham district and noticed indications of copper ore. He found the ground open to relocation, because showings of copper were held in low esteem at that time (gold ores and silver-bearing lead ores were desired), and during the next ten years he acquired all or part of 19 claims—some 200 acres. Eight years later Captain De Lamar acquired a six-month option on three quarters of the Wall holdings but subsequently dropped the option. In May 1899, De Lamar purchased a quarter interest for $50,000 selling it later to D. C. Jackling and associates for $125,000. On January 23, 1903, after many fruitless efforts to finance the property, Jackling obtained an option on two-thirds Wall's holdings for $350,000. Jackling then interested Charles M. MacNeil, Spencer

Penrose, and R. A. F. Penrose in the property, and on June 4, 1903, the Utah Copper Company was incorporated for $500,000 in one-dollar shares. In April 1904, the company was reorganized under the laws of New Jersey with a capital of $4,500,000 in ten-dollar shares. Finally, in March 1910, the Utah Copper Company absorbed a neighboring property, the Boston Consolidated mine, thus rounding out its holdings. Now, the Kennecott Copper Corporation is the owner of the mine and the Utah Copper Company is the operating division.

Geology. A mass of monzonite porphyry, a rock closely related to a granite but lacking in free quartz and with feldspar minerals at many points as large as crystals or groups of crystals in a mass of fine-grained crystals (porphyritic structure), was intruded into beds of quartzite thousands of feet thick and containing a few strata of limestone. As the porphyry mass cooled and solidified, it became fractured, with some large and many tiny cracks, much as you see in a crackled china dish. From the subterranean reservoir or magma, a second flow, this time of mineralizing solutions, penetrated the porphyry mass and deposited the copper minerals. Later, surface waters percolated into the top of the mass and through chemical action dissolved the copper minerals, only to redeposit the copper on original copper minerals deeper down in the mass, thus forming a secondarily enriched ore deposit.

The deposit has an over-all length northeast and southwest of about 6,000 feet, a maximum width of 4,000 feet, and a maximum thickness of about 1,500 feet. The capping or leached porphyry above the ore averaged about 115 feet in thickness, although in places it is only 20 feet thick. An analysis of the copper-bearing minerals and the amount and copper content of the minerals are given in Table V.

Very roughly the ore body is in the shape of a funnel, unusually broad at the top, the whole being distorted from a circular to an elliptical form. Bingham Canyon cuts into the porphyry mass in a roughly north and south line, leaving most of the ore to the west of the canyon, but with enough ore on the east side, in East Mountain, to make that section worth mining. This part of the mine has been opened only recently.

Vehicular Tunnel. In extending mining operations to East Mountain, it was necessary to destroy the automobile road leading up Bingham Canyon from the town of Bingham to the town of Copperfield. However, traffic had to be continued, and so it was decided to drive a vehicular tunnel under the ore in East Mountain. This is a single-lane concrete-lined tunnel 18 feet 2 inches high by 16 feet 4 inches wide with a 3-foot 10-inch elevated pedestrian lane on one side. About half of the tunnel is on a curve. Traffic is controlled by a semaphore light at each end, and no car waiting at the portal is to enter the tunnel until after the red light has turned to green. After a definite time the lights are reversed. The tunnel is 7,000 feet long and rises 450 feet on a 6.43 per cent grade.

There are three turnouts to allow for an emergency such as a flat tire or a stalled engine. An eight-blade Aerodyne fan is placed at one side of the tunnel at the upper or south portal. This fan will handle 150,000 cubic feet of air per minute and is driven by a 60-horsepower 440-volt a-c motor. The fan is controlled automatically by carbon-monoxide indicators in the tunnel. As soon as the concentration of carbon monoxide reaches 3.5 parts in 10,000 parts of air, a circuit is opened, starting the fan and closing a drop door at the upper portal. The fan remains in operation until the carbon monoxide drops to 1.5 parts in 10,000, when the circuit is closed, the drop door is raised, and the tunnel is again ready for traffic. The time of construction was 22 months, and the cost about $1,400,000.

Sampling. The first attempt to explore the ore body was by means of underground workings. Later churn and diamond drill holes were put down at various points on the surface to outline both the horizontal and vertical extent of the deposit. The results from diamond drilling were unsatisfactory, because of the discrepancy between the assays of the core and of the sludge, and so this method of sampling was discarded, and prospecting was done thereafter by means of churn drills. Light drill rigs were used for holes not more than 1,000 feet deep, and standard oil-well rigs were used for deeper holes. Holes need to be cased or lined with pipe to prevent the ground from caving into the holes. At intervals of depth, it is necessary to change to a smaller-diameter casing, because the frictional resistance of the ground against the casing makes it impossible to drive the original size of casing down to the bottom of a deep hole. When a casing becomes "frozen" or immovable, a smaller pipe is run down inside, and a smaller drill is used to continue the hole. A four-inch casing is the smallest through which a satisfactory sample can be taken (a $6^1/_4$-inch would be better); consequently a deep hole

Table V. Analysis of Copper-Bearing Minerals

Amount and Copper Content of Minerals

Mineral	Quantity as a Per Cent of All Copper Minerals	Copper Content of Mineral (Per Cent)
Chalcopyrite	80	34.5
Chalcocite	9	79.8
Covellite	7	66.4
Bornite	4	63.3

Table VI. Tons of Waste Carried by One Ton of Ore

Grade of Ore (Per Cent Copper)	Tons of Waste
0.6	0.5
0.644	1.0
0.688	1.5
0.732	2.0
0.776	2.5
0.820	3.0

is started with a large-diameter casing so that it will not be necessary to reduce the casing below four inches to attain the desired depth. One hole, 1,300 feet deep, was started with a 23-inch casing and ended with a $6^1/_4$-inch casing; the intermediate strings of casing were 20-inch, $15^1/_2$-inch, $12^1/_2$-inch, and 10-inch. A hole 1,469 feet deep required 455 days of elapsed time to drill. The average drilling rate was 3.92 feet per day, and the average progress was 3.23 feet per day. Cost of hole was $20.49 per foot.

To guard against the walls of the hole caving and affecting a sample, drilling is not carried more than 50 feet below the bottom of the casing. Samples are taken in five-foot lengths. They are recovered by a suction bailer run into the hole on a steel cable. The sludge of water and crushed ore brought up by the bailer is divided into several samples. One goes to the mine office for assay, a second goes to the mill-assay office, and a third sample is kept to be mixed with the subsequent nineteen five-foot samples to make a composite 100-foot sample as a check. This sample is assayed and also is subjected to an experimental flotation test. Holes are drilled as nearly as practicable at the apexes of equilateral triangles. The spacing of holes in material of fairly uniform value is 400 feet, but this distance is reduced to 200 feet as the limits of the ore body are approached.

Outlining the Ore Body. The first step in determining the limits or outline of the ore body is to calculate the point of cutoff, under existing conditions of costs and market price of copper. Cutoff is the lowest grade of ore that can be mined and yet pay its way. Obviously most of the ore body must be of higher grade if a profit is to be made. As a preliminary estimate, one-half a ton of waste was assumed to be moved per ton of ore, and the point of cutoff was found to be 0.6 per cent copper. Since more than one-half a ton of waste may have to be moved per ton of ore for parts of the ore body, Table VI may be set up showing the tons of waste that could be carried by ore of various grades.

By the help of this table it is possible to make drawings of various sections of the ore body. Lines are drawn upward and outward from the bottom of the deposit, and from these lines the amount of capping to be removed can be calculated. The ore body decreases in value outwardly from the main body, and the boundaries of the deposit are determined by assays rather than by any sudden geologic change from ore to valueless rock. Horses or masses of waste material are found within the ore body. Its disposition depends on its copper content. Thus, if material assayed 0.55 per cent copper and 0.6 per cent is the point of cutoff, sending this material to the mill would entail a loss of seven cents per ton as against a cost of ten cents per ton for sending it to the dump; hence it would be of advantage to send this material to the mill.

A second factor to consider is the slope of the boundary lines in relation to the angle of repose of the material. If we assume, for example, that the lines on the two opposite sides of a vertical section of the ore body slope up and out at 45 degrees to the horizontal, or on a one to one slope, it may be that the sides of a pit of this slope would not stand unsupported; that is, the angle of repose of the material might be 35 degrees. (It was as low as six to seven degrees at some points along the Panama Canal, where the material was like wet clay.) In this case the walls would slide into the pit; consequently it would be necessary to flatten the slopes to at least 35 degrees. This would mean that more capping than first calculated would have to be removed, and the enterprise might prove to be unprofitable. For these reasons, the grade of ore, amount of capping to be removed per ton of ore, and the angle of repose of the ore and capping must all be considered in outlining an ore body. Also the dip of faults, fractures, and bedding planes have an important effect on the over-all slope of pit sides.

Mining Method. Mining was started on the side of the mountain by cutting a bench along the mountain side and then putting other benches (or levels) below and above the first bench. Thus, the mountain side can be likened to a series of gigantic steps or terraces, the over-all slope from the top bench to the bottom being as low as 28 degrees at some points.

There are 23 benches or levels, beginning with *A* level as the lowest or bottom level, and passing 1,500 feet up the slope to the top. The *A* level is at elevation 6,340, the same as that of the railroad yards where trains are made up for taking ore to the mills. The ore extends downward some 1,000 feet below the *A* level, but in ever-narrowing cross section like the neck of a funnel. As benches are cut below the *A* level, they will be at 50-foot intervals and will be designated by their elevation, as 6,240, 6,190 level, and so on.

The most economical height of individual bench (or bank) is 50 feet, but some banks are higher than this. The minimum width of bench is 70 feet. The face of a single bank may be as steep as 40 degrees, but the over-all slope of the pit sides can be kept to 28 degrees by adjusting the width of the various benches. When all the ore has been removed, the excavation will be in the form of an elongated bowl some 8,000 feet long, 6,000 feet wide, and 2,500 feet deep.

Handling Waste. The stripping or capping is sent to the various dumps. The rugged topography at and around the mine makes the problem of finding sufficient dumping space for the large volume of capping an acute one. Tracks for handling waste are laid at the ends of the various levels. If the distance to a waste dump is not great, a track is run directly to the dump. However, if the dump is far away, the tracks from two levels may converge into one long waste track. At present the average length of waste haul is $2^3/_4$ miles. Waste is carried in side dump cars, of 30 or 40-cubic-yard ca-

pacity, whose dumping mechanism is operated by compressed air.

Drilling and Blasting Ore. The present method of drilling and blasting has been developed through a process of evolution. Hammer drills, driven by compressed air, are mounted on tripods and drill holes into the toe or bottom of the banks. These holes are about 25 feet deep and are bottomed a little below grade to insure breaking the ore to the desired depth. They are about 15 feet apart and are pointed from 5 to 15 degrees below the horizontal. Variations in conditions may call for changes in drilling procedure. In some cases down holes are also drilled near the top edge of the bank.

Holes are started with a bit $3^3/_4$ inches in diameter and are finished with a $1^1/_2$-inch bit. These holes are too small to hold enough powder to break the bank and must be "sprung" or enlarged by firing progressively larger charges in them until a chamber large enough to hold a full charge is made. The springing shots may consist, for example, of 7, 15, 30, and 50 sticks of low-freezing ammonia dynamite. Water is used for stemming so that the holes will not be filled with dirt. The chambered hole will take from 150 to 250 pounds of dynamite, which is loaded through a $1^1/_2$-inch pipe. The shot is fired by means of a primer consisting of one stick of dynamite with a number 6 cap connected to six feet of fuse.

Banks should be blasted well in advance of the power shovels. The material beyond the radius of operation of the shovel should not be blasted, and no loose material should be thrown onto the railroad tracks. Also, the ore should be broken so that there are few if any pieces so large that they have to be broken to smaller size (secondary blasting). After a shovel had loaded the broken ore, the banks are trimmed of loose material. Pieces likely to fall are loosened by bars, and other partly loose material is shot down by a charge of from 15 to 30 sticks of dynamite. On the average about one eighth of a pound of dynamite is used per ton of material broken.

Electric Shovels. In the early days of electrification, steam shovels were converted into electric shovels, some with a-c drive and others with d-c drive. All new shovels are now of the fully revolving type, with d-c motors and Ward-Leonard control. The motor–generator sets on these shovels take alternating current at 5,000 volts and supply the operating motors with 550-volt direct current. Each shovel receives power through 500 feet of insulated cable, which is hooked onto the power line. The cable is carried on a reel on the rear end of the shovel and permits the shovel to move about 400 feet parallel to the bank. All shovels are mounted on caterpillar treads, thus enabling them to back up quickly in case the bank threatens to slide down onto the shovel. Incidentally, the reason for limiting the height of banks to 50 feet is that this is about the maximum height for safe operation. Higher banks are too dangerous.

Shovels are provided with five-cubic-yard dippers. The loading capacity of a shovel is about 19 tons a minute, and so it would be possible to load 9,120 tons of ore in an eight-hour shift if empty cars could be supplied as fast as needed. Since cars are supplied in trains of 10 to 12 cars of 80 to 100 tons capacity each, an interval of time must elapse before a loaded train can move out, and an empty train can move up to the shovel. The loading time for a shovel is about 78 per cent of the elapsed time, and thus its actual loading rate is 7,113 tons per shift. The company has 37 shovels in all, but not all are working at the same time. Operations are on the basis of about 1,200 shovel-shifts a month.

Haulage. Fifty steam locomotives able to haul seven to ten empty cars weighing 21 tons up a four per cent grade at a speed of six to ten miles per hour were replaced by 75-ton electric locomotives ballasted to weigh 85 tons. These locomotives can pull 10 to 12 cars up a four per cent grade (the maximum grade on the switchbacks) at 12 miles per hour. This is the normal speed for a trolley voltage of 675 volts. To make them adaptable to the various conditions throughout the mine, the locomotives are provided with a main overhead pantagraph collector, two side-arm collectors, and a cable reel holding 2,000 feet of cable. Two locomotives are provided with storage batteries for running some distance beyond the end of the trolley wire.

The trolley wire is direct-suspended in the pit, and a special catenary suspension is used elsewhere. Because spreaders are used to push snow over the banks, all permanent poles are placed on the inside of the track at these places. Extra long bracket arms are used and the pull-over messenger wire is placed at the end of the arms. On bridges an *I*-beam structure, two posts, and an overhead crossbeam are used. For tracks passing over large dumps or fills a special construction is used, since the fills may settle as much as 25 feet. The trolley poles are supported on long ties, which settle with the track and maintain a fixed distance between the trolley wire and rails.

On the benches, where trolley supports have to be moved every 30 days, and where flying rocks from blasts may strike poles, the most satisfactory support was found to be portable steel towers 27 feet high, mounted on a skid base six feet long. This tower can be picked up and moved by a locomotive crane. Some structural members can be broken by flying rocks; yet the tower will still support the trolley wire. These towers also carry the three-phase 5,000-volt line supplying power to the shovels.

The speed of the locomotives is directly proportional to the voltage, and so sufficient feeder capacity is provided to prevent an excessive drop in voltage. The

feeder system is so designed that six locomotives, operating on three levels, are supplied from two sources by two feeders. Sectionalizing switches are placed at the ends of the levels so that any level can be cut off in case of line trouble.

Main-line trains to the concentrating plants are hauled by 320-ton steam locomotives of the Mallet type. The 50-car train carries 5,000 tons of ore. Trains must be braked nearly all of the 18 miles because of the 21/2 per cent downgrade; consequently the wear of brake shoes is high.

Electric Power. Power is obtained from the Utah Power and Light Company at 130,000 volts. At the Magna control station it is transformed to 44,000 volts, and a three-phase line extends to Bingham 14 miles distant. At various stations around the mine the voltage is stepped down as needed. Thus, the compressor plant requires 440 volts for its synchronous motors; 5,000 volts are used for the shovels, 2,300 volts are required for the pumps, and the 700-volt d-c current for the electric locomotives is supplied from rotary converters. About 17,000 kw are used at the mine, distributed approximately as follows:

For shovels 20 per cent.
For electric haulage 47 per cent.
For compressed-air plant 16 per cent.
For shops and miscellaneous purposes 6 per cent.
For leaching and precipitation 12 per cent.

The Utah Copper Company is building a power plant that will be ready for operation in October of this year. The 50,000-kw steam turbine (coal or gas will be used as fuel) will not supply all the power needed for mine and mills, and so some 30,000 kw will still be required from the Utah Power and Light Company.

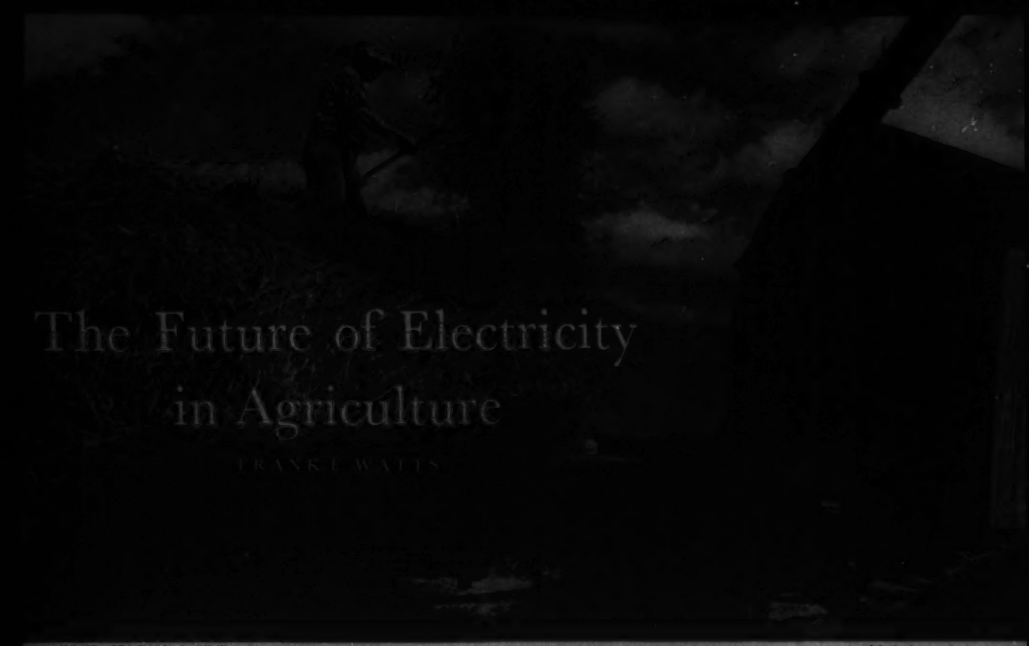
Leaching Plant. Much of the capping contains small amounts of copper chiefly in oxidized form. Ordinarily this copper would be lost when the capping is sent to the dumps. However, by pumping water onto the dumps and letting it percolate down through the capping, enough sulphuric acid is formed to dissolve the greater part of the copper. The copper-bearing solution is drawn off at the bottom of the dumps and is sent through pipes to the precipitating plant, where it passes over detinned scrap iron (waste in the manufacture of tin cans) placed in launders or long troughs. The copper is precipitated in metallic form as cement copper. Slightly more than one pound of iron scrap is required per pound of cement copper. The cement copper, in the form of a red mud, is washed out of the launders, by means of a hose, into tanks, where much of the water is drained off. The mud is loaded into cars by a crane using a clam-shell bucket, and the cars are taken to the Garfield smelter of the American Smelting and Refining Company. In this way the last possible amount of copper is recovered from the low-grade ore.

Courtesy *Mining and Metallurgy*

Bingham Canyon, Utah, cars filled with copper ore bound for smelter

The Future of Electricity in Agriculture

FRANK E. WATTS



Westinghouse photo

In postwar agricultural production electricity is destined to be a tremendous force. First postwar market for electrical appliances will be the farm, says this author, and food and agriculture will be a predominating influence in the making of the permanent peace to follow the war. The electrical industry should recognize the importance of this developing market and prepare to cope with agriculture's problems.

AN ACRE of land is to the farmer what a machine is to a manufacturer—the greater the production, the greater the return on investment. This is the basic idea today in agricultural development.

New crops and greater production of older crops per acre are making rapid strides. In the past ten years the yield of corn per acre has grown from 26.5 bushels to 35.5; of cotton, from 173 pounds to 275; of wheat from 13.1 bushels to 19.8. In 1942 the farmer produced 36 per cent more food on 22,000,000 less acres than 1932, with less man power, but more mechanical and electrical power.

On December 31, 1942, according to Edison Electric Institute statistics, 2,486,230 farms in the United States were receiving electric service from power lines. The average revenue per farm east of the 100th meridian where irrigation was no great factor was $48.07—about 30 per cent greater than that of the average urban customer. This farm revenue is pitifully small when we survey the possibilities of labor saving and increased production by applications of electricity to performing many farm jobs. A great many farms are paying from $100 to $400 annually and *making it pay*. Why then has this market not been developed further by the electrical industry? It is evident that, by and large, selling technique has not been all that it should be.

If the electrical industry is to realize potential sales in this market, it is necessary that there must be a better understanding of the farmer and modern farming. More must be known about agriculture, which after many generations is entering rapidly into a new era of development.

For many generations farming was carried on in the same pattern. Ground was plowed and tilled in much the same manner. There was some improvement in tools and implements used, but little progress was made in productive efficiency. The first and main objective was subsistence. The farmer was isolated, his work was hard, his hours were long, and his standards of living had not kept pace with those of urban dwellers.

As a result, too often his best help as well as his boys and girls left the farm for the city. Many farmers did likewise, and these were replaced by a poorer class of successors whose primary object was subsistence. Surplus depended very much upon seasonal weather and

Essential substance of a conference paper presented at the AIEE national technical meeting, Cleveland, Ohio, September 2–4, 1943.

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management. Today the agricultural industry is undergoing a great change. Boys and girls no longer want to leave the farm. Standards of living are much higher, and the farm is a more attractive place to live. In the first World War a higher percentage of farm boys was rejected by the armed forces than any other class because of poor teeth. As a result of this discovery, dentifrices took a great upward trend in sales to farm people. Rejections of farm boys in World War II are small in comparison and are a direct reflection of higher standards of living due to enlightenment. Today a higher percentage of college and university students in relation to population come from farms than from urban centers. In the year preceding the present war, 538,000 students were enrolled in agricultural schools and colleges.

The farmer himself has become a business man. Better classes of people are being attracted to farms. As a result, agriculture is today on the highest plane it has ever attained in our history. No longer is farming looked upon as simply hard work in producing crops, but as a highly skilled profession.

The food shortage has made urban people more conscious of the farmer, his problems, and how much they are dependent upon him. This recognition is bound to bring "town and country" closer together in a greater bond of sympathetic understanding. Recruiting boys and girls to work on farms in the war emergency will also have its constructive effect in creating this understanding.

The first step to bring the farmer into closer contact with the business and industrial world was the advent of rural free delivery of mail. Then the telephone became available; then the automobile, which brought better roads, enabling him to market his products better, and keep in closer touch with his markets; and finally the radio and motion pictures. All these forces have combined to keep the farmer in close touch with a world which affects his welfare. Work of county agents and other services of the Department of Agriculture have been most constructive also, and the importance of their work is mounting at a rapid rate. Agricultural Colleges, the 4-*H* Clubs, the Future Farmers of America, the American Farm Bureau Federation, The National Grange, all are contributing to a great forward movement in agriculture.

Table I. Cost and Savings Data for a Typical Farm Electric Water System

1.	Gallons of water pumped	100,000
2.	Cost of pump and installation	$107.00
3.	Cost of electric annually (3 cents per kilowatt-hour)	$ 3.00
4.	Total cost of system and electricity for first year	$110.00
5.	Hours required to pump by hand (75 gallons per hour)	1,333
6.	Days required to pump by hand (10-hour day)	133.3
7.	Cost at $2 per day	$266.60
8.	Saving one year (over total cost of system and electricity)	$156.60
9.	Maintenance and cost of electricity after first year	$ 8.35
10.	Annual saving after first year, per year	$258.25

SCIENCE AND POWER

The forces which are bringing about an evolution almost approaching proportions of a revolution in agriculture are primarily science and power. Recognition of the possibilities of the application of these forces by enlightenment is bringing the farmer out of his isolation.

Great strides are being made in chemurgy—farm crops grown for industrial uses. Wheeler McMillen, president of The National Chemurgic Council and editor-in-chief of *Farm Journal*, said in his annual address before the council on March 24, 1943:

"The proportion of usable wealth to be derived from an acre's production is becoming larger. From its initial concept, chemurgy has meant *maximum utilization of maximum production*. It has insisted that ways be found to use the high as well as the low values of the harvest—the stalk as well as the grain, the shell as well as the kernel, the weed as well as the crop."

At a meeting of this same council on March 27, 1942, L. F. Livingston, manager of the agricultural extension division of E. I. DuPont DeNemours and Company said:

"Scientific research is responsible for more improvement in living conditions in the United States than any other thing. The results have benefited agriculture, industry, and consumers alike. Nearly everything we use nowadays is touched by chemistry. Living conditions are being revolutionized.

"The American chemical industry has prospered in good and bad times alike, because it has had the courage to spend money to find ways of producing more and better goods for less money. A similarly constructive approach to the problems of farming will increasingly produce better varieties of grains and fruits, improved farm machinery, control of soil-borne diseases, breeding of higher-production animals, and more efficient pest-control measures that will save growers millions of dollars now being lost.

"There is no limit to the factory stomach to be fed by the farm; the partnership between the farmer and the manufacturer is a close one, much closer now than most of us realize. And as we fill the arsenals in the struggle to hold our freedom, the farmer can see perhaps a quarter of a century's normal advance toward a new and more prosperous era telescoped into a few years."

Gunstocks are made from soybeans, cotton seed, and corncobs. Life preservers are made from the floss of milkweed; other substitutes for kapok are being developed from cattail fibers; plastics from cotton; from the castor bean have been developed new insecticides so badly needed; from the castor bean also is derived oil for the production of a host of critical implements of war, from tanks and bombers to cannon; rubber is now being produced from Kok-sagyz and guayule plants.

This is but a small list of new farm products used by industry. In the future, and in some instances now, crops will be grown to specifications; not just wheat, but wheat of a predetermined character; long fiber cotton is already being grown to specification. The farmer will grow not only the grains from which cereals are made, but also the products from which are made the materials for packaging such cereals. Industry and agriculture are being drawn closer together in a bond of

mutual interest, and this augers well for both. Henry Ford recently said, "The partnership of farm and industry has just begun."

AN ERA OF MECHANIZATION

As a result of these social and economic forces, the first great advance in agricultural production came with mechanization following World War I. The tractor with its related implements, its adaptability for doing by power many hard jobs more speedily and more economically has represented a great step in productive efficiency.

We must recognize that the problem of the farmer parallels that of the manufacturer in this respect. Industry by mechanization in the last generation has multiplied many times the output per man. This has resulted in greater production of more goods at less cost. The possibilities of this same productive increase are equally as great in agriculture—more goods at less cost through powered labor-saving devices. It has been said that it may be entirely possible to cut farm production costs from 25 to 50 per cent. We must recognize the depth of the forces bringing about great changes in agriculture if we are intelligently to approach the sales problem of selling the farmer. Today the great trend is toward more production per acre through scientific and power applications. Increased production per acre at less cost is the watchword of the farmer.

ELECTRICITY AS A PRODUCTIVE FORCE

In the field of power applications for productive efficiency, electricity is destined to play the leading role. No longer does the farmer want electric service primarily for its comfort and convenience, but for its great adaptability for doing jobs for labor-saving and increased production. The future will bring new applications, new devices as yet undreamed of. The electrical industry may well devote its great engineering resources to a more intensive study of the business of farming. It is only through such engineering research that we can attain the knowledge which will enable the industry to develop its great potential possibilities. We must know farm people better, we must have a greater understanding of their problems if we are to be of help in solving these problems.

Some of our large industries do not hesitate to spend a million dollars or more on research in the chemical industry, in electronics, or in plastics. Yet agriculture, representing by far the greatest investment of any industry, has been badly neglected. Agricultural income is far greater than any other—$16,138,319,000 in cash marketings in 1942. To this must be added approximately $2,000,000,000 from investments and work done off the farm and another $2,000,000,000 for food grown and consumed on the farm. This is more than seven times the income of all our electric utilities. Research work in this field has lagged probably because of the great number of farm units—over 6,000,000—whereas research in the chemical industry as an example is confined to a relatively small group. Farming will have to be broken down as to different types, and studies made of each group, depending upon the nature of crops produced or other farm operations.

While rural electrification is not by any means new, the market was more or less "spotty" and did not attract the sales and promotion activities of the industry generally until about 1936. Prior to that time, most of the promotion work was done by electric utilities. They laid the foundation for the great interest being manifested today. The impetus now apparent is such that farm people will not be denied all the comforts, conveniences, labor saving, and increased production effected by electric service. Of greatest significance is the possibility of cutting production costs through applications of electricity.

There are over 200 known uses for electricity on the farm. An analysis is made of one of the most important uses to illustrate labor savings as well as other resultant increases in production. These savings have been reduced to man-hours and dollars and cents savings estimated. These statistics, are based on actual known costs, and a sufficient degree of conservatism is applied to make the estimates safe for actual application.

ELECTRIC WATER SYSTEM

The first and one of the greatest labor savers is a water system. The example given in Table I is for a definite unit of gallonage pumped and may be reduced or expanded in relation to needs. Cost of the system, depreciation, and cost of operation are shown. The latter is based upon actual installation, the cost of which has been determined.

This direct saving in dollars does not reflect by any means all the benefits of an electric water system. Milk production is increased from 10 to 24 per cent. Cows need plenty of water—about 25 gallons per day—at frequent intervals, and drinking fountains provide this water at proper temperatures. Cows will not drink sufficient cold water for maximum milk production.

Two actual cases of increased production are here cited. The first consisted of a herd of 23 Jersey cows. For the first six months prior to installation of a water system 12,511 pounds of milk were produced. In the six-month period after the installation 15,628 pounds were produced—an increase of 3,117 pounds or 24 per cent. In the same instance, there was an average increase of 17.7 pounds of butter fat per cow.

In the second case, 15,634 pounds of milk and 507 pounds of butter fat were produced in the 30-day period preceding the water-system installation. The 30-day period following showed a production of 19,995 pounds of milk and 686 pounds of butter fat. This increase was maintained in the months following and represented an increase of 28 per cent in milk and 35 per cent in butter

fat. This meant an increase of over $1,550 in revenue annually, provided the same number of cows milked monthly is maintained. This does not consider revenue from increased butter fat. The figures seem so fantastic as to be almost incredible.

This saving in the dairy does not by any means reflect all labor or production savings. Equally impressive data may be shown for the poultry house, the barn, the home, for vegetable gardens, and many other applications. The data given are sufficient, however, to emphasize the possibilities.

"THE PROOF OF THE PUDDING"

One of the most complete records that has been kept in determining operational costs of electricity for farm jobs was that of Niagara, Lockport, and Ontario Power Company on the Brundage Farm at Oakfield, N. Y. Records were kept for five years, and the data given in Table II are taken from the last year ending October 1939. Statistical data on which the operational costs were based are as follows:

Number in family—3 adults, 3 children
Size of house—12 rooms
Type of farm—Dairy, poultry, and crops
Acres—185
Cattle kept—36
Milking cows—18-26
Horses—4
Laying hens—1,100
Pullets raised—1,200
Baby chicks sold—13,000
Crops grown—Oats, corn, hay, potatoes, beans

The electric rate schedule was:

First 12 kilowatt-hours per month	$1.50 net
Next 48 kilowatt-hours per month	4½ cents per kilowatt-hour
Next 140 kilowatt-hours per month	2½ cents per kilowatt-hour
Excess over 200 kilowatt-hours per month	1½ cents per kilowatt-hour

The data in Table II are by no means complete as to detail in the report itself, but they show

1. The great amount of work accomplished by electricity.
2. The potentiality of the farm as a consumer of electricity.
3. The potentiality as a market for appliances and devices.

It will be noticed first that the yearly bill was more than that of nine urban customers based upon 1942 national average. A total of 6,484 meals was served at a cost of $6.67 per person per year, or 55 cents per month; 6,490 gallons of water were heated at 53:7 cents per person per month; the refrigerator cost ten cents per month per person; 306 individual washings were done at a cost of 89 cents per year, and the ironing was done for 86 cents. In the poultry house an average of 617 hens was lighted, and 1,145 received warm water—24,300 eggs were placed in incubators, and 15,350 chicks hatched, hovered, and brooded. In the dairy an average of 20.2 cows was milked—15,560 gallons of milk were cooled—442,000 gallons of water were pumped—the ventilating system was used 1,041 hours; 120 tons of ensilage were stored at 2.3 cents per ton; 4.05 tons of feed were ground at 36.5 cents per ton; 83 tons of hay and straw were hoisted at a total cost of 36 cents. These data confirm the fact that electricity is the cheapest thing the farmer buys.

We might go on and on with illustrations of what electricity does in the saving of time and labor. Those given, however, should suffice to give us a concept of the approach to a greater application to farm jobs. But we must not overlook one very important phase of this work, that is, the uplifting influence of lightening the labor of human beings. The morale of farm people is enhanced beyond measure by this new force in their lives. Farming takes on a new dignity, and pride in their profession adds new zest to that strength of character which has always been theirs as one of the most solid segments of our national life.

Table II. Yearly and Average Monthly Consumption and Cost of Energy for Individual Home and Farm Applications on An Experimental Farm

Average Cost Per Kilowatt-Hour—1.817 Cents

Application	Yearly Kilowatt-Hour Consumption	Yearly Cost	Average Monthly Kilowatt-Hour Consumption	Average Monthly Cost
Entire farm	18,897	$343.38	1,575	$28.61
Residence	7,455	135.46	621	11.29
House lighting and small appliances	2,588	47.02	216	3.92
Range	2,201	39.99	183	3.33
Water heater	2,129	38.68	177	3.22
Refrigerator	395	7.18	33	0.60
Ironer	17	0.31	1.5	0.03
Iron	30	0.55	2.5	0.05
Washer	49	0.89	4.1	0.07
Radio	46	0.84	3.9	0.07
Poultry farm	5,766	104.77	481	8.73
Poultry house lights	349	6.34	29	0.52
Poultry water warmers	698	12.68	58	1.05
Incubators	2,990	54.33	249	4.52
Battery brooder	286	5.20	24	0.44
Hover brooders	1,192	21.66	100	1.82
Miscellaneous lights	155	2.82	13	0.23
Shop	96	1.74	8	0.15
Dairy farm	5,445	98.94	454	8.24
Barn lighting	832	15.12	70	1.27
Milking machine	1,024	18.61	85	1.54
Dairy-utensil scalder	1,235	22.44	103	1.87
Milk cooler	1,118	20.31	93	1.69
Water pump	1,105	20.08	92	1.67
Dairy ventilating fans	131	2.38	11	0.20
Portable motor	231	4.20	19	0.35
Silo filling	130	2.36	10.9	0.20
Feed grinding	81	1.48	6.7	0.12
Hay hoisting	20	0.36	1.6	0.03

FARM WIRING

No discussion of this subject would be complete without reference to the importance of a good and adequate wiring system. Good practice dictates today that the distribution center should be so located that service may be most economically and satisfactorily carried to all farm buildings. The farmer who installs electric service should be made to understand the necessity of providing for greater future use. For this reason, adequate copper, both in feeder and branch circuits, should be of such size as to take care of additional load without the need of overhauling the wiring system. The original cost, when the system is first installed, is so small that all the farmer needs is an explanation of its desirability. He is a close buyer but he wants the best. He needs dependable service, and maintenance men are not just around the corner for him.

New farm uses for electricity are not far away. Arc welding, television, dehydration, sharp freezing, and frozen-food storage are some new developments now ready for exploitation. Frozen foods alone present one of the greatest opportunities the electrical industry has ever had. Electronics, in which so much research and experimental work is now going on, offers a tremendous opportunity in plant breeding and propagation. The more agriculture is studied, the wider becomes the horizon for electric service. The wiring system is the very heart of extension of both service and market for appliances and devices. Instead of the average wiring installation being $50, it should be $300 to $500.

FIRST POSTWAR MARKET IS THE FARM

In the postwar period the most immediate market for electrical appliances is the farm. There are three sound reasons for this statement:

1. During the war, when the farmer has been called upon for his greatest production with less man power and equipment, he has learned as never before what electricity means as a *productive* force.

2. The urban industrial worker will be conservative about spending his savings until he finds himself safely in a peacetime job. On the other hand, the farmer will be called upon for at least five years for an even greater production to feed food-famished countries. He therefore has no fears about investment in all kinds of new equipment.

3. The farmer has more money than he has ever had. It is reliably estimated that there will be a farm market for new buildings, repairs, and equipment of $12,000,000,000 in the first two years following the war. The farmer does not have to wait for the money to do this work—he has it *now*.

The electrical industry should get at least ten per cent of this market, but this cannot be done except by better distribution, better sales plans, more promotion, and more advertising. Now is the time to prepare for one of the greatest and one of the most immediate markets. New sales techniques based upon *investment* in labor saving and increased production equipment and appliances must be developed. Know farm jobs better, and sales will be easier and far greater. We have not scratched the surface of possibilities of producing more farm products at less cost by greater applications of electric service.

LOOKING FORWARD

In conclusion, there is another most important reason for the extension of electricity to the business of farming. In the making of a permanent peace following the war, food will be the predominating influence. The American farmer will be called upon for many years for full production. Unless this problem of food is solved successfully, there can be no lasting peace.

This situation has been analyzed as having three distinct periods. The first is relief, when food must be provided quickly for millions of people already starving. Stable governments cannot be founded on riots and revolution which breed on starvation. The second period is defined as that of rehabilitation, when occupied countries as well as those of the United Nations must be provided with machinery and tools, that they again may revive their own agricultural production. The third period is that of reconstruction, wherein agriculture will be developed through greater productive efficiency. This period may take a generation or more, but the American farmer must always keep in the forefront of lowered production costs if he is to compete with cheaper labor of other countries. Otherwise trade barriers which will surely lead to another war will be established.

In a long-range as well as a short-range plan for productive efficiency, electricity can be made a tremendous force. It is not only an opportunity but a responsibility of the entire electrical industry to devote to the fullest its research, its engineering, and its sales ability to the solution of a problem which so fundamentally affects the future welfare of the American people. There can be no prosperity in this country unless agriculture is prosperous—it goes hand-in-hand and side-by-side with industrial production. The harvest, indeed, is rich, and the rewards will come in greatest measure to those who realize and capitalize on the industry's opportunity number one. Not only will we be of service to the American farmer but to the future welfare and peace of our own country and that of the world.

Westinghouse photo

This oil circuit breaker in use on rural-line crossarms automatically recloses twice after opening on short circuit, thus restoring service instantly on the majority of short circuits and maintaining a high degree of service continuity. It has no steel tank but uses the porcelain bushing not only as insulation but as a container for the interrupter and the oil

Evaluation of Incompletely Diversified Loads

W. L. TADLOCK
MEMBER AIEE

IT IS relatively simple to determine the average demands of any particular electric load, but such average data are practically useless for the design of an electric distribution system. Voltage regulation is the factor limiting load on most distribution system components. For this reason, these components can be designed intelligently only on the basis of the recurrent maximum demands of their loads. To the author's knowledge, no proper method of determining such demands has been used previously by electrical engineers. This article presents a method of determining the most probable values of such load demands.

This load-analysis method was developed during the last three years, in order to determine the *pertinent* diversified demands of standard (National Electrical Manufacturers Association) single- and twin-unit 30-gallon uncontrolled electric water heaters. These data, which are not generally available, were secured from field load tests made in Alabama and Georgia in 1939–40. Analysis of the comparative field data on these two heaters indicated that they were essentially equal: in their ability to give water heating service; in their total annual cost to the residential customer; and in their desirability as domestic load.

Intelligent distribution-system design is dependent on proper evaluation of incompletely diversified loads, says this distribution engineer. Such a method of load analysis is set forth in this article.

The majority of the domestic electric load in the southeastern states is composed of lighting, refrigerating, cooking, and water heating equipment. Single-unit uncontrolled electric water heaters furnish the hot water service in most cases. Figure 17 of this paper indicates the most probable recurrent maximum demands which any particular number of these heaters will impose on electric facilities. These recently determined data, along with currently available data on electric lighting, refrigeration, and ranges are indicated on Figure 18. With these empirical data, plus knowledge of the physical location of the domestic loads to be served, the electrical performance of any distribution-system component can be readily calculated.

This load-analysis method can be used to advantage in interpreting properly all electric loads that are not fully diversified. Other domestic loads such as lighting and ranges, commercial-lighting and power loads, and lighting and power loads in military establishments, probably could be served with the use of materially less investment or strategic materials, if their average recurrent maximum demands were better known. It is hoped that this article will contribute to that end.

SERVICE REQUIREMENTS OF UNSTABLE OR INCOMPLETELY DIVERSIFIED LOADS

The capacity of electric distribution systems is usually determined by voltage-drop limitations. In general, this is true where the smallness of the load prohibits the use of voltage regulators. In such cases, the equipment heating effects of the loads involved are relatively unimportant, but it is of first importance to know the magnitude and occurrence frequency of the maximum voltage drops which these loads cause.

Capital investments during peacetime, or the use of strategic materials during wartime to care for those maximum peak loads which occur only occasionally, cannot be justified. Electric-service facilities that will not have excessive voltage drops for those peak loads which recur as often as approximately once every one or two weeks usually can be justified. Greater peak loads than these will occur less often, and smaller peak loads will occur more often. Provision for the larger and less frequent demands is undesirable, whereas the smaller more frequent demands will be served more than adequately by properly designed facilities.

The recurrent demands of loads composed of a relatively small number of load units vary considerably from each other and from their average value. (See Figures 8 and 9.) The demands on distribution-system services have this characteristic most prominently. The progressively better diversified loads on secondary circuits, line transformers, primary feeders, and distribution substations, have this characteristic to a progressively lesser degree.

A GENERAL METHOD OF PROPERLY EVALUATING INCOMPLETELY DIVERSIFIED ELECTRIC LOADS

Figure 13A and Table I illustrate a general method of determining the weighted average value of those maximum distribution-system demands which recur

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Based upon and developed from a paper presented initially at the conference on analysis of military loads and postwar application, AIEE winter technical meeting, New York, N. Y., January 25–29, 1943.

sufficiently often to justify system capacity to serve them. In addition, Table II illustrates a general method of determining unknown total or *composite* load values of demand and their recurrence frequencies, from known *component* load values. Both of these supplementing load-analysis methods are based on the use of the class frequency-distribution polygon.[1] In Figure 13A, the assumed occurrence frequency or probability of demands in any particular two-kilowatt demand interval is plotted against the mid-point of that particular demand interval. If sufficient demand data on any particular load can be secured from actual field tests, the characteristics of that load can be determined definitely from the corresponding demand frequency-distribution polygon.

The individual demands of such a polygon are mutually exclusive. Therefore the probability that some *one* of any particular number of demands will occur equals the sum of the individual probabilities (ΣP) corresponding to those particular demands. The weighted average value of those maximum demands having any particular total probability of occurrence, therefore, equals the sum of the moments of the individual demand probabilities about the zero-demand axis, $\Sigma(DP)$, divided by the sum of the individual demand probabilities, ΣP. This average-maximum-demand value will be referred to hereafter as $D_{\text{avg max}}$. In Table I, all values of $D_{\text{avg max}}$ [equal to $\Sigma(DP)/\Sigma P$] within the limits of the assumed data are calculated. The results are indicated graphically in Figure 13A by the curves marked "days." The value of the $D_{\text{avg max}}$ recurrence period in days (equal to $1/\Sigma P$) is used as being more significant than the total occurrence probability ΣP.

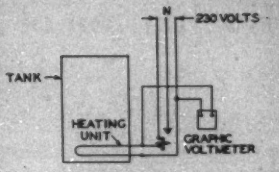


FIGURE 1

Figure 1. Schematic connection diagram used for load tests on NEMA standard 30-gallon single-unit 1,500-watt electric water heaters. Graphic voltmeter connected for 230-volt operation

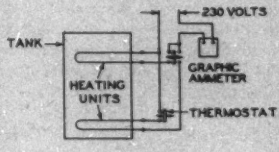


FIGURE 2

Figure 2. Same as Figure 1, except for twin-unit heaters with 600-watt bottom unit and 1,000-watt top unit electrically interlocked for 1,000-watt maximum demand. Graphic ammeter records loads

Table I. Determination of the Average of the Recurrent Maximum Demands, Whose Total Probability of Occurrence (or Frequency of Recurrence) Is Any Desired Value, From Complete Demand Versus Frequency Data.* Results Indicated Graphically in Figure 13A

D* Diversified Demand (Kw)	P* Probability (%/100)	DP	ΣP	Σ(DP)	Average Maximum Demands (Kw) Σ(DP)/ΣP	Maximum-Demand Recurrence Period (Days) 1/ΣP
For 5 Water Heaters						
7	0.035	0.245	0.035	0.245	7.00	28.6
5	0.193	0.965	0.228	1.210	5.31	4.39
3	0.422	1.266	0.650	2.476	3.81	1.54
1	0.350	0.350	1.000	2.826	2.83‡	1.00
For 10 Ranges						
17	0.01	0.17	0.01	0.17	17.0	100.
15	0.02	0.30	0.03	0.47	15.7	33.3
13	0.05	0.65	0.08	1.12	14.0	12.5
11	0.10	1.10	0.18	2.22	12.3	5.56
9	0.17	1.53	0.35	3.75	10.7	2.86
7	0.22	1.54	0.57	5.29	9.28	1.76
5	0.19	0.95	0.76	6.24	8.22	1.32
3	0.15	0.45	0.91	6.69	7.35	1.10
1	0.09	0.09	1.00	6.78	6.78‡	1.00
For 5 Water Heaters and 10 Ranges**						
24	0.00035	0.00840	0.00035	0.00840	24.0	2860.
22	0.00263	0.0579	0.00298	0.0663	22.2	336.
20	0.00983	0.197	0.01281	0.263	20.5	78.1
18	0.02509	0.452	0.03790	0.715	18.9	26.4
16	0.05335	0.854	0.09125	1.57	17.2	11.0
14	0.10021	1.40	0.19146	2.97	15.5	5.22
12	0.15585	1.87	0.34731	4.84	13.9	2.88
10	0.19426	1.94	0.54157	6.78	12.5	1.85
8	0.18928	1.51	0.73085	8.29	11.3	1.37
6	0.14717	0.883	0.87802	9.17	10.5	1.14
4	0.09048	0.362	0.96850	9.53	9.83	1.03
2	0.03150	0.0630	1.00000	9.60	9.60‡	1.00

* All examples of values of D and P are for mid-points of two-kilowatt load intervals.

** See Table II for an example of the general method of calculating unknown composite load values of D and P from known component load values of D and P.

‡ Average daily demand.

The demands of a group of five electric water heaters are independent of the demands of a group of ten electric ranges. By considering the assumed demands for such independent loads (graphically indicated in Figure 13A and tabulated in Table II), it can be seen that any one of the four heater demands may concur with any one of the independent nine range demands, or, there are 36 possible coincident or composite demands. However, the probability of occurrence of any one of these 36 possible composite demands, D_h+D_r, equals the product of the corresponding component demand probabilities, P_hP_r. Similarly, for three or more groups of mutually independent electric loads (such as heaters, ranges, lighting, . . .), the probability of any particular component load-demand concurrence, $D_h+D_r+D_l+\ldots$, is the product of the corresponding component load probabilities, $P_hP_rP_l\ldots$. A composite load-demand frequency-distribution polygon may be determined from sufficient data on the component loads as follows:

1. Determine all of the possible sums of the component load demands, $D_h+D_r+D_l+\ldots$.
2. Determine $P_hP_rP_l\ldots$ for each of the values $D_h+D_r+D_l+\ldots$.
3. Group the values of $D_h+D_r+D_l+\ldots$ by demand intervals of proper size (one or two kilowatts). Thereafter use the mid-point

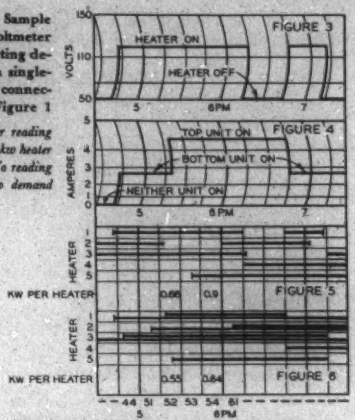


Figure 3. Sample graphic voltmeter chart depicting demands of a single-unit heater connected as in Figure 1

Any voltmeter reading indicates 1.5-kw heater demand. No reading indicates zero demand

Figure 4. Sample graphic ammeter chart depicting demands of twin-unit heater connected as in Figure 2

Upper reading indicates 1,000-watt top-unit demand. Lower reading indicates 600-watt bottom-unit demand. No reading indicates zero demand

Figure 5. Condensed graphical summary of coincident load data for five single-unit heaters

Heavy horizontal lines indicate heaters "on," at 1.5 kw each. Breaks in lines indicate heaters "off." Line 1 indicates load data of Figure 3. By adding and interpreting the horizontal "load lines" crossing each vertical time column, the diversified 15-minute demand, per heater, for a group of five heaters was secured, as indicated at bottom of two sample columns

Figure 6. Same as Figure 5, except for five twin-unit heaters

Line 1 indicates load data of Figure 4. Doubled horizontal lines indicate 1,000-watt upper-unit operation. Single lines indicate 600-watt bottom-unit operation. No line indicates inoperative heater

value of any particular demand interval to designate all values of $D_h+D_r+D_l+\ldots$ falling in that interval.

4. Add values of $P_hP_rP_l\ldots$ corresponding to all values of $D_h+D_r+D_l+\ldots$ falling in the same demand interval.

5. Plot values of $P_c=\Sigma(P_hP_rP_l\ldots)$ corresponding to each composite load-demand-interval mid-point, D_c. The result is a representative composite-load-demand frequency-distribution polygon.

Such a composite-load polygon, for two component loads (heaters and ranges) is determined in Table II and illustrated at bottom of Figure 13A. $D_{avg\ max}$ for this calculated composite load, is determined at bottom of Table I and illustrated by the curve marked "days" at the bottom of Figure 13A.

Composite, or total, residential-load values of $D_{avg\ max}$ are the ones for which line-transformer secondary-circuit combinations must be designed. However, with the aid of the two previously outlined load-analysis methods, these composite-load demands can be determined adequately from considerably less component-load-demand data than composite-load-demand data. For instance, adequate demand data on composite residential loads (measured at line transformer) consists of representative demand data on all of the possible combinations of, say, 1, 5, 10, 20, and 30 residential lighting loads; 1, 5, 10, 20, and 30 ranges; and 1, 5, 10, 20, and 30 water heaters. Assuming that there cannot be more ranges or water heaters than lighting customers, on a particular circuit, there are still 50 different possible combinations of these component loads for which representative composite-load-demand data (measured at the line transformer) would have to be secured. In other words, the necessary data for the construction of approximately 50 composite-load-frequency polygons would be required in order to evaluate properly the various residential load demands on line-transformer secondary-circuit combinations. Compared with this, representative-demand data on only five different-sized groups of lighting loads, five different-sized groups of range loads, and five different-sized groups of heater loads (15 total component-load groups) are required. Actually, all component-load data required can be determined from representative-demand data on 30 individual lighting customers, 30 individual ranges, and 30 individual water heaters (90 total individual-load units). As residential loads are physically distributed, demand data on individual lighting, range, or heater loads, rather than on grouped loads, are inherently easier to secure. Adequate demand data on 30 individual component-load units can be combined numerically, as described later in this article, to give the diversified-demand data required for groups of 1, 5, 10, 20, or 30 component-load units.

In order to determine $D_{avg\ max}$ for all representative composite residential loads, approximately 50 composite-load-frequency polygons must be finally determined in either case. If composite-load demands are metered at the line transformer, a relatively large amount of field-test data, but relatively little computing labor, is required. If the demands of individual component-load units are metered, a relatively small amount of field-test data, but a relatively large amount of computing labor, is required.

RESIDENTIAL LOAD DEMANDS DETERMINED FROM LIMITED FIELD-TEST DATA

Even adequate component-residential-load data are quite difficult to secure. When such data are not too meager, however, composite-load demands can still be determined with reasonable accuracy by employing a modified form of the general methods outlined. An example of the use of these modified analysis methods is given in Table III. The limited component-load data and the calculated composite-load demands are illustrated in Figure 13B.

The essential difference between the general and modified analysis methods is that in the general method, the component-load-frequency polygons are determined by plotting the variable probability values against the

corresponding constant-demand-interval mid-points, while in the modified method, the component-load polygons are determined by plotting a constant value of demand-occurrence probability against the corresponding variable values of the individual recurrent demands. In the modified method, the constant value of probability equals one divided by the number of individual recurrent demands in the limited data, or, it is assumed that within the limits of the available data, each recurrent-demand value has the same weight, or probability of occurrence.

On this basis, as indicated in Table III and illustrated in Figure 13B, the probability of all individual composite demands is also a constant, equal to the product of the two or more constant component-demand probabilities. Component-load values of $D_{avg\ max}$, determined by the modified method, equal the simple numerical average of those maximum demands having a total probability of occurrence ΣP equal to nP (where n equals the number of maximum demands averaged and P equals the constant probability of each individual demand).

Table II. Calculation of Composite Load Demands (D_c) and Their Occurrence Probabilities (P_c) From Known Demand and Occurrence-Probability Data for Two Component Loads (Five Water Heaters and Ten Ranges). Data Further Analyzed in Table I and Illustrated in Figure 13A

D_h* Diversified Demand (Kw)	D_r* Diversified Demand (Kw)	D_c* (D_h+D_r) (Kw)	P_h* Probability (%/100)	P_r* Probability (%/100)	P_hP_r
1	1	2	0.35	0.09	0.03150
1	3	4	0.35	0.15	0.05250
1	5	6	0.35	0.19	0.06650
1	7	8	0.35	0.22	0.07700
1	9	10	0.35	0.17	0.05950
1	11	12	0.35	0.10	0.03500
1	13	14	0.35	0.05	0.01750
1	15	16	0.35	0.02	0.00700
1	17	18	0.35	0.01	0.00350
3	1	4	0.422	0.09	0.03798
3	3	6	0.422	0.15	0.06330
3	5	8	0.422	0.19	0.08018
3	7	10	0.422	0.22	0.09284
3	9	12	0.422	0.17	0.07174
3	11	14	0.422	0.10	0.04220
3	13	16	0.422	0.05	0.02110
3	15	18	0.422	0.02	0.00844
3	17	20	0.422	0.01	0.00422
5	1	6	0.193	0.09	0.01737
5	3	8	0.193	0.15	0.02895
5	5	10	0.193	0.19	0.03667
5	7	12	0.193	0.22	0.04246
5	9	14	0.193	0.17	0.03281
5	11	16	0.193	0.10	0.01930
5	13	18	0.193	0.05	0.00965
5	15	20	0.193	0.02	0.00386
5	17	22	0.193	0.01	0.00193
7	1	8	0.035	0.09	0.00315
7	3	10	0.035	0.15	0.00525
7	5	12	0.035	0.19	0.00665
7	7	14	0.035	0.22	0.00770
7	9	16	0.035	0.17	0.00595
7	11	18	0.035	0.10	0.00350
7	13	20	0.035	0.05	0.00175
7	15	22	0.035	0.02	0.00070
7	17	24	0.035	0.01	0.00035
Totals			7.000	4.00	1.00000

Calculated Composite Values for Five Water Heaters and Ten Ranges**	
D_c* (D_h+D_r) (Kw)	P_c* $\Sigma(P_hP_r)$ (%/100)
2	0.03150
4	0.09048
6	0.14717
8	0.18928
10	0.19426
12	0.15585
14	0.10021
16	0.05335
18	0.02509
20	0.00983
22	0.00263
24	0.00035
Total	1.00000

* D_h, D_r, and D_c represent heater range, and composite (heater and range) demands, respectively. P_h, P_r, and P_c represent heater, range, and composite demand occurrence probabilities, respectively.

** For any particular value of D_c, P_c equals $\Sigma(P_hP_r)$. For example (D_c = 6.0 kw), P_c = (0.0665+0.0633 +0.01737) = (0.14717).

SUM OF TWO OR MORE COMPONENT-LOAD VALUES OF $D_{avg\ max}$ APPROXIMATELY EQUAL TO $D_{avg\ max}$ FOR COMPOSITE LOAD

A study of particular sets of component-load data, which were analyzed by means of the modified analysis methods, indicated that a component-loads contribution to the composite-loads $D_{avg\ max}$ varies with the sizes of the other component loads. For example, the part of $D_{avg\ max}$, on a line transformer, caused by five water heaters, is somewhat less when the transformer also serves ten ranges than when the transformer also serves just five ranges.

This being the case, it follows that composite-load values of $D_{avg\ max}$ cannot be determined *exactly* from

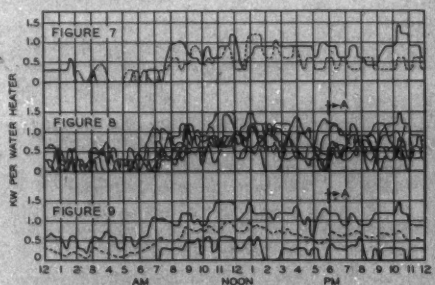


Figure 7. Example of how distribution-system component load curves do not repeat themselves even for same day of week

Solid curve represents diversified 15-minute kw demands, per heater, for a group of five 1,500-watt single-unit water heaters on one Saturday. Dotted curve is for same heaters on following Saturday

Figure 8. The same data as Figure 7, except for seven five-heater groups on successive Saturdays

Figure 9. Example of how distribution-system loads for a particular day vary from the average load for that day

Solid lines are envelope of the maximum and minimum 15-minute demand values of Figure 8. The dotted line represents the average heater demands of Figure 8

component-load values of $D_{avg\ max}$. For example, by referring to Figures 13A and 13B, it is seen that those composite-load values of $D_{avg\ max}$, which occur every n^3 days, are from zero per cent to nine per cent larger than the sums of the heater and range values of $D_{avg\ max}$ which occur every n days. However, until sufficient load data have been analyzed to determine the previously described composite-residential-load-demand polygons (for approximately 50 combinations of component loads) we have no choice but to approximate composite-load values of $D_{avg\ max}$ from available data on component-load values of $D_{avg\ max}$.

In distribution-system design this approximation appears to be sufficiently accurate for all practical purposes.

ACTUAL DETERMINATION OF DIVERSIFIED WATER-HEATER DEMANDS FROM FIELD-TEST DATA

In the winter of 1939–40, 15-minute demand data on 34 heater-weeks of single-unit water-heater operation and 34 heater-weeks of twin-unit water-heater operation were secured in Alabama and Georgia (see Figures 1–4). Single- and twin-heating elements were alternated in the same heater tanks (serving the same customers) for these tests. Test data on these heaters also were secured during the summer of 1939, but as the winter demands were found to be roughly 50 per cent greater, due to the lower winter inlet-water temperatures, only the winter demands were analyzed further.

The graphic-meter-chart data were condensed, for further analysis, on lengths of cross-section paper as indicated in Figures 5 and 6. Twenty-four-hour time scales were laid out horizontally by a code numbering of 96 consecutive columns to correspond to the 96 quarter hours per day.

After the 34 heater-weeks of graphic-meter demand data were condensed in this manner, they were subdivided into seven groups of five heater-weeks per group (demand data on one heater-week was used once, in each of two groups, in order to complete the seventh five-heater group from 34 heater-weeks of data). Then, the diversified demands of each of the seven groups were determined for each 15-minute period of each day of the week by adding and interpreting the horizontal "load lines" crossing each time column (see Figures 5 and 6).

Actual winter Saturday diversified-demand curves for five-heater groups of single-unit water heaters are indicated in Figures 7 and 8.

After the diversified demands, per heater, were determined for the seven five-heater-week groups, the diversified demands, per heater, for ten-heater-week groups were determined by averaging the diversified demands of two five-heater-week groups (by adding these demands and dividing the sums by two). Diversified demands for four ten-heater-week groups were secured, in this way, from four pairs of five-heater-week groups. The four pairs were formed by using six of the seven groups, once each, and one of the seven groups, twice. Similarly, the diversified demands, per heater, for three 20-heater-week groups were determined from the diversified demands per heater, of the four ten-heater-week groups.

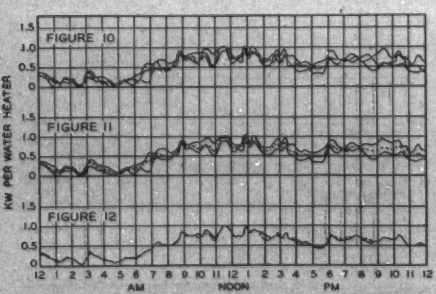
Actual winter Saturday diversified-demand curves for 20-heater groups of single-unit water heaters are indicated in Figure 10.

ACTUAL DETERMINATION OF $D_{avg\ max}$ FOR WATER HEATERS

Comparison of diversified heater demands, for the various days of the week, disclosed that there was considerable variation in these daily demands, even for the same time of day. For instance, Thursday heater demands were considerably greater at time of distribution-system peak demand (5:45 p.m.) than any other day's demands.

In view of this day-to-day variation, values of $D_{avg\ max}$ for water heaters (for each 15-minute period of the day) were determined first for each day of the week and then for the entire week by averaging the daily values. The numerical average of six of the daily values of $D_{avg\ max}$ (for each 15-minute period of the day) was determined as being the most probable component of the distribution-circuit $D_{avg\ max}$ caused by water heaters. Hereafter, week averages of daily values of $D_{avg\ max}$ will be referred to as $D'_{avg\ max}$. Because Sunday heater demands were relatively low, they were not used in determining values of $D'_{avg\ max}$. The author now does not believe this omission was proper, however.

Because we analyzed heater demands by individual days of the week, the data which we could use to determine values of $D_{avg\ max}$ were limited to only one seventh

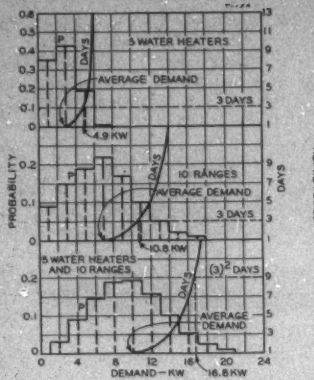


Figures 10 and 11. Same as Figures 8 and 9, respectively, except curves for three 20-heater-group Saturdays. These curves illustrate the increase in stability of diversified loads with increase in number of load units per load group

Figure 12. Solid and dotted curves, respectively, are the average-demand curves of Figures 9 and 11. These curves illustrate the fact that the average demands, per load unit, for a five-load-unit group and any other sized group, are identical

Figure 13A. Top and center of figure are assumed diversified demand-frequency versus demand-interval polygons for a group of five water heaters and for a group of ten ranges during the period 5:45-6:00 p.m. on Saturday. Bottom of figure indicates the calculated frequency versus demand-interval polygon for the composite heater and range demands at the same time on that day

Curves, labeled "days," indicate the average value ($D_{avg\ max}$) of those maximum demands which have the indicated recurrence period in days. The recurrence period of one day, on these curves, coincides with the average daily demand (or the average of those demands which recur every day). The value of the composite load $D_{avg\ max}$, recurring every n^3 days, equals approximately the sum of the component load values of $D_{avg\ max}$ recurring every n days. For example, the composite load $D_{avg\ max} = 16.8$ kw, recurring every nine days, approximately equals the sum of the heater load $D_{avg\ max} = 4.9$ kw and the range load $D_{avg\ max} = 10.8$ kw, each recurring every three days



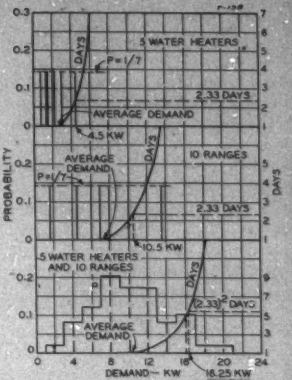


Figure 13B. Same as Figure 13A, except top and center of figure depict data so limited in quantity that a special form of frequency–demand diagram is employed, wherein individual recurrent demands, instead of demand-interval mid-points, are plotted. Top of figure depicts the actual recurrent Saturday total water-heater demands corresponding to those indicated in curve form in Figures 8 and 9, at Section A-A. Center of figure depicts assumed similar data for ten electric ranges

$D_{avg\ max}$ can be determined, from data in this form, by simply averaging the desired number of the recurrent maximum individual demands, as indicated and justified in Table III

of the total. However, reasonably stable values of $D_{avg\ max}$ were determined from these data by means of the modified analysis method, previously described (see Figure 13B and Table III).

To determine actual values of $D_{avg\ max}$ for water heaters, the unweighted average of those recurrent maximum demands, representing 3/7 of the total number of recurrent demands, was calculated. In line with previously outlined principles, the total occurrence probability of this number of recurrent maximum demands is 3/7, or once every 2.33 days. Assuming that equivalent data on electric-range and lighting-load demands are available, the composite- (or distribution-circuit) load values of $D_{avg\ max}$ (approximately equal to the sum of the lighting, range, and heater values of $D_{avg\ max}$) would recur every $(2.33)^3$ days, or approximately every 12 or 13 days. This maximum-demand recurrence period is approximately correct for design purposes.

To determine $D_{avg\ max}$ per water heater, for each 15-minute period of each day of the week we:

1. Averaged the 15 recurrent maximum demands, constituting approximately 3/7 of the 34 total recurrent demands, for one heater.

2. Averaged the three recurrent maximum diversified demands, constituting 3/7 of the seven total recurrent diversified demands, for groups of five heaters (this is illustrated, for Saturday demands, in Table IV).

3. Took the weighted average of the first maximum demand and 5/7 of the second maximum demand (added first demand to 5/7 of second demand and divided sum by 1 5/7) constituting 3/7 of the four total recurrent diversified demands, for groups of ten heaters.

4. Took the weighted average of the first maximum demand and 2/7 of the second maximum demand, constituting 3/7 of the three total recurrent diversified demands, for groups of 20 heaters.

After values of $D_{avg\ max}$ had been calculated, for each 15-minute period of each day of the week, their unweighted Monday–Saturday week average was calculated, for each 15-minute period of the day. As previously explained this value of $D'_{avg\ max}$, for each 15-

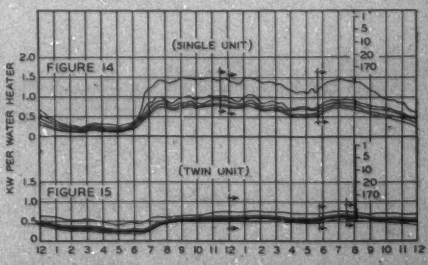


Figure 14. $D'_{avg\ max}$, or winter, week averages of the daily average maximum diversified demands ($D_{avg\ max}$) of single-unit 1,500-watt 30 gallon NEMA standard uncontrolled electric water heaters, in 1, 5, 10, 20, and 170 heater groups

Figure 15. Same as Figure 14, except demands ($D'_{avg\ max}$) of twin-unit NEMA standard water heaters, having 600-watt bottom units and 1,000-watt top units, with units interlocked for 1,000-watt maximum demand

minute period of the day, was considered to represent the most probable component of the distribution-circuit $D'_{\text{avg max}}$ caused by water heaters. Figures 14 and 15 depict the calculated values of $D'_{\text{avg max}}$ for single- and twin-unit water heaters. The curves on Figures 14 and 15, for 170 heater-days (5×34 heater-days), depict the Monday–Friday week-average demands of the average water heater. By comparing the curve of $D'_{\text{avg max}}$ for 20 heaters, with this curve of the average demand of the average heater it can be seen that the values of the former are only slightly greater than the values of the latter. We may conclude from this that the demands of 20 water heaters are almost completely diversified.

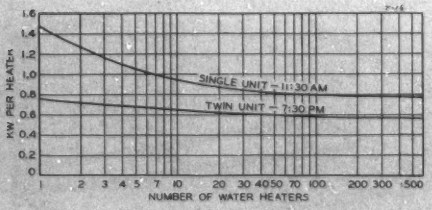
The values of $D'_{\text{avg max}}$ on Figures 14 and 15 are presented in more usable form in Figures 16 and 17.

RELATIVE CHARACTERISTICS OF SINGLE- AND TWIN-UNIT UNCONTROLLED HEATERS

Examination of Figures 16 and 17 discloses that the values of $D'_{\text{avg max}}$ for uncontrolled single-unit heaters are larger than those for equivalent uncontrolled twin-unit heaters. However, examination of Figures 14, 15, and 17 discloses that this difference is not so great, at the time of the circuit peak (5:45 p.m.).

Analysis of the comparative 1939–40 field-test data, on single- and twin-unit NEMA standard 30-gallon uncontrolled electric water heaters, indicated in general that:

1. The two heaters gave essentially equal domestic water-heating services.



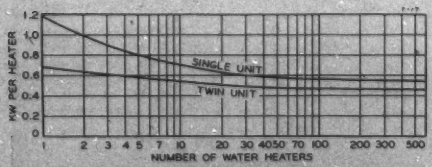


Figure 16. Winter average maximum demands ($D'_{\text{avg max}}$) of various numbers of water heaters, from "peak demand" cross sections of 24-hour demand curves of Figures 14 and 15

Figure 17. Winter average maximum demands ($D'_{\text{avg max}}$) of various numbers of water heaters, at time of distribution-system peak demand (5:45 p.m.). Data from 5:45 p.m. cross sections of Figures 14 and 15

2. The single-unit heater had greater demands (see Figures 16 and 17) and required approximately six per cent more energy than the twin-unit heater.

3. The single-unit heater was simpler and had a lower first cost than the twin-unit heater.

4. The sum of the domestic customer's operating and fixed costs was essentially the same for the two heaters.

5. The two heaters were equally desirable domestic loads.

6. It is possible to exercise "partial off-peak control" of the twin-unit heater at some reduction in heating capacity, a function not possible with the single-unit heater.

DESIGN OF DOMESTIC ELECTRIC-SERVICE FACILITIES

The values of $D'_{\text{avg max}}$ for various numbers of single-unit uncontrolled electric water heaters, determined by the modified analysis method outlined herein, is now being used in several of the southeastern states in the design of domestic electric-service facilities. These calculated data, along with modified empirically determined data for electric ranges,[2] refrigerators,[3] and lighting and miscellaneous demands,[4] were assembled on one curve sheet for use by distribution engineers in

Table III. Same as Table I, Except for Limited Field Data. Results Indicated Graphically in Figure 13B

D Diversified Demand (Kw)	P Probability (%/100)	DP	ΣP	Σ(DP)	Average Maximum Demands (Kw) Σ(DP)/ΣP	Maximum-Demand Recurrence Period (Days) 1/ΣP
For 5 Water Heaters*						
6.00	1/7	6.00P	1P	6.00P	6.00	7.00
4.50	1/7	4.50P	2P	10.50P	5.25	3.50
3.00	1/7	3.00P	3P	13.50P	4.50**	2.33
2.25	1/7	2.25P	4P	15.75P	3.94	1.75
1.50	1/7	1.50P	5P	17.25P	3.45	1.40
1.50	1/7	1.50P	6P	18.75P	3.12	1.17
0.75	1/7	0.75P	7P	19.50P	2.79‡	1.00
For 10 Ranges*						
13.6	1/7	13.6P	1P	13.6P	13.6	7.00
10.0	1/7	10.0P	2P	23.6P	11.8	3.50
8.0	1/7	8.0P	3P	31.6P	10.5**	2.33
7.0	1/7	7.0P	4P	38.6P	9.6	1.75
6.0	1/7	6.0P	5P	44.6P	8.9	1.40
4.5	1/7	4.5P	6P	44.1P	8.1	1.17
1.7	1/7	1.7P	7P	50.8P	7.26‡	1.00
For 5 Water Heaters and 10 Ranges‡‡						
20	0.0204	0.408	0.0204	0.408	20.0	49.0
18	0.0204	0.368	0.0408	0.776	19.0	24.5
16	0.102	1.63	0.1428	2.41	16.9	7.00
14	0.0816	1.14	0.2244	3.55	15.8	4.46
12	0.1736	2.08	0.3980	5.63	14.1	2.51
10	0.1736	1.74	0.5716	7.37	12.9	1.75
8	0.2044	1.63	0.7760	9.00	11.6	1.29
6	0.122	0.732	0.8980	9.73	10.8	1.11
4	0.0816	0.326	0.9796	10.1	10.3	1.02
2	0.0204	0.0408	1.0000	10.1	10.1‡	1.00

* $\Sigma(PD)/\Sigma P$ reduces to $(\Sigma D)/n$ for these limited data wherein D represents individual recurrent demands instead of demand-interval mid-points. n is the number of maximum-demand values whose average value is to be determined.

** Average maximum demands having $\Sigma P = 3/7$.

‡ Average daily demand.

‡‡ Composite load demands and probabilities (for 5 heaters and 10 ranges) determined by simply counting the number of possible sums of $(D_A + D_r)$ which fall in each of the ten two-kilowatt demand intervals. The number of sums in each demand interval multiplied by $\{1/49 = (1/7)(1/7)\} = \Sigma P_h P_r = P_n$.

Table IV. Diversified Recurrent Saturday 15-Minute Kilowatt Demands, Per Heater, for Groups of Five Single-Unit Water Heaters.* Individual and Average Saturday Demand Data Indicated Graphically in Figures 8 and 9

Heater Group—Saturdays														
	1	*0.60*	*0.60*	*0.45*	0.30	0.90	*1.02*	*1.32*	*1.20*	*1.20*	*0.90*	*0.60*
	2	0.30	0.12	*0.30*	*0.30*	0.84	*1.02*	*0.30*	0.30	0.60	*0.90*	*0.90*
	3	0.00	0.00	0.00	0.12	0.57	0.30	0.30	*0.60*	0.60	*0.60*	0.30
	4	0.30	*0.30*	0.06	0.00	*1.14*	0.90	0.00	0.15	0.42	0.30	*0.78*
	5	*0.30*	0.15	0.00	0.00	0.54	0.30	0.06	0.45	*0.75*	0.30	0.30
	6	*0.60*	*0.60*	0.12	*0.30*	*0.90*	0.90	*0.90*	*0.90*	*1.14*	0.30	0.30
	7	0.00	0.00	*0.45*	*0.60*	*1.47*	0.66	0.30	0.30	0.48	0.60	0.30
Sum of Three Maximum Demands		1.50	1.59	1.20	1.20	3.51	2.94	2.52	2.70	3.09	2.40	2.28
Average of Three Maximum Demands ($D_{avg\ max}$)		0.50	0.53	0.40	0.40	1.17	0.98	0.84	0.90	1.03	0.80	0.76
(96) Coded 15-Minute Time Periods		121	122	54	61	114	121	53	54	61	113	114
		12		6 a.m.		12 noon		6 p.m.			12	

**Italic* figures indicate the three maximum demands, in seven recurrent Saturdays, for a particular time of day.

† Column of data, corresponding to total demands, analyzed in Table III and illustrated at top of Figure 13B.

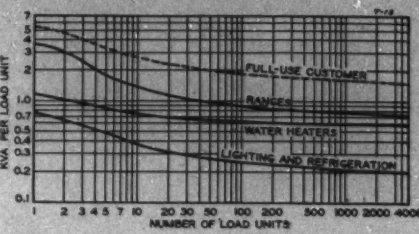


Figure 18. Most probable values of average maximum diversified demand ($D'_{avg\ max}$) for residential customers, electric ranges, and electric water heaters. Dotted curve indicates demands of "full use" customers, all of whom have lights and refrigerators, ranges, and water heaters. These data are based on 100 per cent electric-refrigerator saturation as representative of the majority of new residential customers

determining the composite, or total, load values of $D'_{avg\ max}$. These complete demand data are indicated in Figure 18.

With the load data indicated in Figure 18, and knowledge of the physical location of the domestic load to be served, the electrical performance of any electric distribution-system component can be readily calculated.

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4. Reference 2 ,page 17.

Wood beams top steel columns in this 26-kv wartime-built substation of the Public Service (N. J.) Electric and Gas Company

Wartime Trends in Arc Welding

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Arc welding has made considerable progress in the past several years, much of it as a direct result of the war. The contributions made by the three big factors in arc welding—technique, electrodes, and machines—to the development of the science are evaluated in this article.

ONE of the strangest inconsistencies in our modern industrial world is that, although we consider ourselves the most progressive people in the world, a wonderful tool or a revolutionary improvement will often lie unrecognized, unclaimed, and unsupported, until we are forced by war or national catastrophe to examine and use it. Oftentimes the torch of this work has been carried by some toiling inventor, often by a little-known but determined organization, and many times by some farseeing industrialists.

Such was the story, in a sense, of arc welding. Its story has been a rough and stormy one, not always pleasant. Electric arc welding, like aviation, got its first real opportunity during World War I, but, unlike the American planes which did get to the front and show their merit, very few arc-welded products ever came within the sound of battle—most of them were still in the assembly stage when the armistice brought to an end the four long years of World War I. As a result, welded ships were almost 20 years away, welded tanks 24 years, welded railcars 16 years.

But in passing these milestones, the science of arc welding has grown beyond the wildest dreams of its pioneers. Today every column of welding statistics looks like a pyramid; all of the graphs run off the top edge of the sheet while dollar volume has had a habit of doubling itself every year recently.

In 1938, only a little more than five years ago, electric welding was an $18,000,000 industry. According to the best estimates, sales of arc-welding equipment exceeded $128,000,000 in 1942. Of this sum, over $46,000,000 was spent on new machines. Back in 1938 industry purchased $4,000,000 worth of new welders. Gas welding, however, during the same period, did not increase anywhere near this proportion. More money was spent in 1941 and 1942 on arc-welding equipment than had been spent in the previous 25 years combined.

Figures and statistics are not very informative at times and really tell us little of true progress in the science of welding with the electric arc.

While the average designer still puts a half-inch fillet where a quarter-inch one would be more than sufficient, and while blueprints even today come into the shop marked for welding on the inside where not even the welding foreman can get his electrode holder, let alone the welding rod, arc welding of today has made much progress. Much of this progress has been a direct result of the war, and, during the course of this discussion we should like to evaluate this progress to date and, in so doing, gain a glimpse of what we may expect from the future.

In arc welding there are three big variables, each dependent on the other, yet each distinct in its own importance—technique, electrodes, and machines. When all three are working together correctly, arc welding is at its best. Success without this mutual co-operation is sheer luck. Let us take these three variables, one by one, and analyze how war has brought improvement to them.

It was not so many years ago when the entire choice of the welding was left to the welder on the job. Such, in fact, is still the case in some plants. Fortunately, for arc welding, the average old-time welder was master of the art, a combination metallurgist, designer, engineer, and magician. His work was often surrounded with much mystery—seldom even did the superintendent question his methods. One of the strangest facts in the history of arc welding was that, while in one plant welding technique was left to luck or to the skill of the welder, another factory doing similar work for years had been making studies and tests of the possibilities of this new fabricating method and was utilizing this knowledge to better its product through scientific design, incorporating as much welding as possible in its product.

When the first *Panzer* divisions overran Poland in September 1939, and Britain and France began to purchase vast quantities of war material in the United States, those plants which had left arc welding for repairs and continued to rivet, bolt, or cast their various parts were beginning to suffer. There is no place on the battlefield for a tank or gun or jeep, that is "almost as good." Most large industries began to buy welding equipment almost frantically, only to find that for some reason or other their welds would crack wide open as they cooled, or would warp and distort the assembly beyond repair. Soon the men in charge began to realize that here was too important a part of production to trust it to luck. The solution—to submit each new

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welded design to a man who knew all about welding. He must be a good engineer, a metallurgist, a cost analyst, and, most of all, a marvelous diplomat and psychologist. Such an individual became known as the "welding engineer." Unfortunately, there were only a few hundred such men in the country. Those plants which needed them most, usually got them. The others are still dependent on the past experience of their personnel and on luck to guide them in the future.

Once given the authority, as well as the responsibility, the welding engineer in charge could begin a cleanup of the bad welding practices in which most plants abound. One of his first problems to overcome was bad welding technique.

Incorrect procedure has been one of the most flagrant errors in modern arc welding. Factories have been known to buy the very best in equipment and then use an electrode several sizes too small, requiring up to 300 per cent more welding time, or to make a series of welds on one joint in the wrong sequence, causing hopeless distortion and warping. As a result, more time is spent in straightening than is spent in welding. Correct procedure can eliminate or greatly reduce this waste of time.

Another source of expensive welding is incorrect welding technique. Most welders have very definite opinions as to the size of rod, angle of the electrode, size of the fillet, for a given weld. Previous to the war, these decisions were generally left to the welder himself. Since the war, however, the labor situation very definitely has taken a turn for the worse. A man (or woman) who can demonstrate that he or she can hold an arc is usually hired on the spot. Obviously, such a class of workmen cannot be left to judge the most efficient technique by themselves. Even at best, a good welder by prewar standards, was not able to judge within ten per cent which combination gave him the minimum spatter, together with maximum speed and penetration and minimum waste of electrode material.

And so both welding procedure and welding technique have been placed under the glass and found wanting as the war began. Fortunately, the welding industry has been able to meet this challenge halfway, and some of those manufacturing plants on which we must depend so greatly for the winning of the war, have placed responsibility for the choice of correct procedure, design, and technique in responsible hands, either the welding engineer or the welding superintendents. Much more of this careful assignment of responsibility, however, is still needed.

Of all the factors entering into an arc weld, none has been surrounded with so much mystery and hokum as the electrodes. In the years preceding the war, most welding rods were sold on a friendship basis. Welding was truly a salesman's paradise. Once the welders and welding foremen were "sold" on the merits of a certain rod salesman, they were immediately "sold" on the electrodes he handled. Everyone and his proverbial brother seemed to be selling rods; yet there were only about 12 large electrode makers. It was not so long ago that many buyers discovered that the only real difference between salesman *A*'s rod and salesman *B*'s rod was that the coating was red instead of green. They both were made in the same electrode plant.

Fortunately, there were a few excellent rods, notably those used for high-pressure boiler work, but most of the rod manufacturers were doing their testing in the customer's plants. When stainless steels started coming into the picture prominently about 1935, it was evident that a tremendous amount of research must be done to manufacture satisfactory stainless electrodes. Coatings on such wires as 25–12 stainless had to be good. Many of the electrode manufacturers realized their responsibility and installed complete metallurgical laboratories for research on future requirements and improvement of their present products.

Such was the picture when war struck home to all of us here in America. Three days after Pearl Harbor the Army tested and passed the first welded armor plate for all-welded tanks. Those first plates were welded with stainless electrodes—incidentally, the same type that only a year or two previously had been developed for use on kitchen equipment and store window fronts.

That was less than a year and a half ago. Yet when Field Marshall Rommel began his retreat in February, destined to be the longest retreat in history, he was retreating in the face of American heavy tanks—all-welded, made only a few months previous. Nothing the Germans could make was a match for the combination of heavy tanks and tank busters, both made from chromium-alloy all-welded armor plate.

The battle for supremacy on the desert was the real proving ground for welded armor plate, and you can be sure it was followed just as closely by the electrode manufacturers as it was by the War Department in Washington. Here truly, welding was winning the war for the United Nations. It might have been a different story if arc welding had remained in the background just a few years longer. Armor welding had not been without its headaches—the biggest one the matter of supply. The unprecedented use of stainless electrodes led to all kinds of problems. Armor plate contains little other than chromium in any quantities, and theoretically, a rod with similar or slightly higher chromium content should do the job. Such was not the case. Invariably, the weld would crack on test. As it stands today, after a year and a half, nearly all armor plate is still being welded with an 18–8 stainless alloy very similar to that used in original tests. In order to reduce the different types of core wire required, many manufacturers are adding some minor alloys, such as molybdenum or manganese as a powder to the coating, so that they will modify the weld metals.

War's greatest effect on electrode manufacture was the unprecedented demand for welding rods of all types.

In 1939 America bought 150,000,000 pounds of electrodes. In 1942 America made an estimated 750,000,000 pounds. The figure will be close to 500,000 tons in 1943. Electrode manufacturers were backlogged several months. Deliveries were averaging three months or more on the more common rods. In order to relieve this problem, the War Production Board ordered many rod makers to discontinue odd sizes and types. Two sizes in particular are practically off the market—$^{1}/_{32}$ inch and $^{7}/_{32}$ inch.

Another very important step was the development by one manufacturer of an electrode suitable for vertical and overhead work on high-pressure boiler work for use with a-c machines. This development eliminated one of the few important advantages which d-c welding had held over competitive a-c welding equipment. Many manufacturers are working on similar rods made from stainless and other alloys which are still more or less closed to a-c welding.

A vigorous campaign has been under way for several months to make the best use of the electrodes that are available. Correct technique cited before has helped considerably. Usage of the full rod length is also an important point. One source estimates that several cargo ships could be built every month with the electrodes saved in using all but $1^{1}/_{4}$ inches of the electrode instead of the customary two-inch stub.

Thus the war has made the welding industry definitely electrode-conscious. Progress in welding rods is now in the hands of the metallurgists and out of the hands of salesmen.

The third big variable in welding is the equipment used. Of the three fields involved, the electrical industry had done the best job of providing machines with which to work.

Equipment breaks down into three classes quite easily: automatic equipment, d-c equipment, and a-c equipment.

Before the war automatic equipment was considered suitable only for large plants. It quickly became obvious that shipbuilding could be speeded up greatly if one-inch plates could be butt-welded in one pass instead of five, and if this single pass could be made automatically. Shipyards were quick to realize these advantages, and automatic equipment spread like wildfire throughout the industry.

Most automatic equipment was used with a-c welding transformers; the average unit furnishing about 1,000 amperes.

Long before Pearl Harbor an excellent line of d-c motor-generators had been developed by the various manufacturers. This type of machine had been the standard welder for many years, and, through constant improvement, had reached a high degree of efficiency and durability. The war brought few changes in this field.

As a direct result of the need for stainless-steel welding in lighter gauges, one manufacturer placed on the market a small electronic type of d-c welder. This unit, made for precision welding, made possible the production welding of stainless and other hard-to-weld alloys on material down to 30- and 32-gauge using $^{3}/_{64}$-inch electrodes. An electronic welder, because of its very quick voltage recovery, is ideally suited to low-current welding.

Crater eliminators or remote-control units were developed as a direct result of the use of arc welding in the aircraft industry. Such devices, operated by the welders' hands or feet enabled him to change current values at will, even during the course of the weld. Their use was limited to d-c machines.

Previous to 1936, a-c welding had been something "good to be against" as many welders put it. Early manufacturers placed transformer welders on the market with little regard for life or limb of the user. Open-circuit voltages as high as 100 volts from electrode holder to ground were common. Occasionally some welder would lose his life, and the news spread fast that a-c welding had killed another man. A-c welding needed heavily coated electrodes, needed them badly if it was to survive. Gradually such electrodes were made available. When these electrodes were used the striking voltage could be reduced to 80 volts or lower, especially at higher amperages. Although much of this early prejudice remains even today, a-c welders comprise a large part of new equipment installations.

Previous to the war, most a-c transformers varied output current by means of a tapped secondary winding or tapped series reactor, or combination of both. The continuously variable welders were quite bulky and were subject to considerable wear on the moving parts.

The war gave manufacturers the impetus to improve their a-c welders. Industrial users, in general, demanded continuously variable equipment, and several types of transformer welder circuits were made available. Re-

cently one manufacturer placed on the market a continuously variable transformer and reactor combination giving a higher open-circuit voltage at the lower amperages which reduces to a lower voltage as the current is increased. This reduced the reactive drop and the resultant power-factor correction involved.

In general, then, electrical equipment is of a high quality. A-c welding, in particular, has expanded greatly because of wartime demands, and every evidence points to still greater utilization of this method.

In going over these present-day trends in the three big factors in arc welding today, we have tried particularly to view them in the light of what we can expect in the future. While the war has undoubtedly forced the arc-welding industry to purge itself of many bad practices, the goal is by no means won. The opportunities presented by arc welding are so vast that we have but scratched the surface. In the days that follow the war, shipbuilding may drop off, but for every one less ship to be welded, there will be a dozen cargo planes, or autos, or prefabricated homes, or pieces of farm equipment to take its place. Outside of the United States, Britain, and Germany, arc welding is practically unknown. The world is hungry for men to build the machines, to form the rods, and to teach the science of arc welding. They will look to America for leadership. Can anyone, realizing this, consider for a moment that welding has reached its limit?

Yes, we need men, welding needs good men, good engineers. For every welding engineer in industry today, at least ten are needed. There are years of research ahead. Only a minimum of the many variables have been standardized. Years of research and hard work lie ahead before we can consider our job done.

And as each new alloy is developed, a corresponding development must take place to provide suitable welding electrodes. There is still practically no real standardization in the electrode field.

As better automatic equipment is made available, power supplies must be furnished to match it. High-frequency arc striking, elimination of the hazard to the operator, higher arc efficiency, greatly reduced weights of welders, are but a few of the improvements needed.

Arc welding has given us some of the best fighting equipment in the world, and it has given it to us faster than anything in history. When peace comes again some day, those same hands that welded tanks and guns and ships will weld our homes, our planes, and our future.

Regional Development Through Industrial Research

LAWRENCE W. BASS

Widespread adoption of technical research is recommended as a vital part of the advance planning necessary to the conversion of industrial resources from wartime to peacetime production.

APPLIED SCIENCE has become a major force in our national and regional development during the past century. Its benefits have been most apparent within the last few decades, with the rise of industrial research. It is not a magic panacea for economic ills, but it is a vital part of any constructive program to prevent or cure them. A country, a region, an industry, or a company which does not take advantage of scientific progress is at best doomed to a disappointing future.

In a section in which there are numerous enterprises of medium and small size, such as New England, the technical programs of many concerns necessarily will be on a less grand scale than among some of our large corporations. Such activities may not conform to a classical definition of research, but they must be present to some degree if the work of scientists and engineers is to bear fruit in the form of new or improved products and novel or better processes.

A helpful concept in understanding the place of research in industry is found in the eight "M's" of successful business, adopted as an editorial philosophy by *Chemical and Metallurgical Engineering*. The four basic requirements are materials, methods, machinery, and motive power. To bring them into action, men and money must be provided. These six "M's" are co-

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ordinated by management, which directs them to the final goal, markets.

The technical man's influence should, of course, be felt throughout the cycle of production. But the opportunity for systematic study, or research, is most apparent in determining the suitability of materials, in developing satisfactory methods, in designing the necessary new machinery, and in adapting the required motive power, so that improved products demanded by the markets can be fabricated. In this way the framework of an industrial structure is erected by which management can profitably guide the productive capacity of men and of money to fruitful ends.

The technical work necessary to maintain industrial activity at optimum levels may be divided into four general headings, which cannot be sharply differentiated. First is *fundamental research*, aimed at the discovery of basic knowledge. This is carried out for the most part in our educational and scientific institutions, but should be sustained on a still greater scale, with more emphasis on regional resources and with sympathetic co-operation from industry in selecting the most promising fields. Secondly, there is *applied research*, directed at the translation of basic information into practical channels. This should be supported by manufacturers to the limit of their ability. Next comes *engineering development*, the implementation of applied research on a commercial scale. Finally, *production control*, involving technical guidance of manufacturing operations, deserves much more attention from industry to insure maximum efficiency in procedures.

In order that these four types of technical activities may be carried out most constructively, the engineer and the scientist must rise to new heights. Their training must not stop at graduation, but they must be given facilities for continued professional improvement throughout their careers. Scientific societies can do much to encourage study groups by means of local and regional programs. Libraries, both public and private, should be stimulated to expand their collections and services. More attention should be given in professional circles to questions of broad economic importance, and the interchange of ideas and philosophies with business executives should be fostered.

There is no royal road by which scientists and engineers can reach a solution of the problems of wartime or of the postwar period. The real answer lies in the adoption of a twofold program—individual initiative on the part of both technical men and management, and the concerted efforts of professional groups toward regional development. To effect the former, every company executive should strive to secure the best possible sources of scientific and engineering knowledge, and every technical man should broaden his vision and seek means by which he can contribute to the general welfare of his community and region. To institute the latter, professional organizations and industry have the reciprocal responsibility of providing a stimulus for and of supporting a universally aggressive technology.

In order that scientists and engineers may best aid in efforts toward regional development, some form of organization is desirable. Committees representing a range of professional groups have been used effectively, normally with subcommittees in special fields to insure widespread participation. It is advantageous to include the social sciences in setting up such boards. Careful thought should be given to the size of the community or district to be included; too narrow a scope may stifle the effort.

An industrial development committee, as it might be called, can be active on both short- and long-range projects. The former, which have the encouraging effect of rapid results, include service as a clearing house for technical information, assistance in finding professional personnel, advice on methods of attacking specific problems, and the encouragement of educational talks before nontechnical audiences. The more elaborate type of undertaking, which imparts depth and permanence to the program, is represented by studies of local resources and industrial facilities, stimulation of pertinent fundamental researches, co-operation in educational policies, and assistance to libraries.

The establishment of committees is, of course, only the initial stage, and the small number of opportunities for service during the early months of the organizations is likely to be discouraging. However, in such an instance, the newly established committee can often profit greatly by a more or less close association with other public service groups. Through judicious publicity, attention and support can be drawn to long-range undertakings and business men can be reminded of the existence of an organization to which they should turn in time of need.

The technical man is not usually endowed with marked gifts in the direction of public relations and contacts. The business man who has had little contact with the professional world tends to expect the impossible, and does not realize that one of the most valuable contributions such a group can make toward solving his difficulties is advice on how he can take steps to help himself. The success of an industrial development committee depends upon the harmonious working together of these complementary business personalities.

The nonprofit Foundation with which I am connected was set up as a practical step toward regional improvement. Our objectives are broad: to aid companies in planning and organizing research programs; to encourage critical surveys of natural resources; to stimulate basic investigations that will provide foundations for new industries; to co-operate with any groups that foster contacts between scientists and business executives; and to serve as a clearing house for information on these subjects. In short, we are doing all we can to help industry to use one of our greatest regional resources—the technical man.

International Standardization

L. F. ADAMS
FELLOW AIEE

IN THESE DAYS international standardization is all but forgotten. Nevertheless, we are giving increased attention to our present and future business relations with South American countries, which are becoming standards-conscious, and after the war renewed activity in standardization on an international scale may be expected. Although one cannot, or should not, predict the developments or exact course such standardization will take, it is reasonable to assume that it will be built upon existing organizations and present accomplishments. Therefore, a brief historical review of two of the international standards-making bodies that are of chief concern to the electrical industry may be of interest. These two organizations are the International Electrotechnical Commission and the International Standards Association. Other organizations, such as the World Power Conference, the International High-Voltage Conference and the International Commission on Illumination serve as engineering forums, and may reveal the need of and produce technical information pertinent to standards, but they do not establish standards.

A brief historical review of two of the existing international standards-making bodies of chief concern to the electrical industry.

In September 1904, the chamber of government delegates met during the International Electrical Congress of St. Louis, Mo., and passed a resolution "that steps should be taken to secure the co-operation of the technical societies of the world by the appointment of a representative commission to consider the question of the standardization of the nomenclature and ratings of electrical apparatus and machinery." As a result of this, and shortly thereafter, the International Electrotechnical Commission was formed, with headquarters in London, England.

Any country may join the IEC upon request by forming a national committee through its technical societies or national standardizing body. For many years, the IEC work in the United States has cleared through the United States national committee of the IEC which was established originally by the AIEE. Upon formation of the electrical standards committee of the American Standards Association in 1931 the two committees were made almost identical. Thereby, close co-operation between national and international standardization in the electrical field was effected.

As was inevitable, the IEC became inactive shortly following the outbreak of hostilities in 1939. At that time it had as members 27 countries, three of which belong to the Western Hemisphere—Argentina, Canada, and the United States. In February 1941, I had a letter from C. le Maistre, director of the IEC, telling that the Commission's offices had suffered rather badly from enemy bombing and that some of the stock of publications was destroyed. However, records and some office equipment had been removed from London and were intact, according to latest information.

The IEC Standards that have been produced amount to some dozen and a half in number. Several of these are of fundamental importance and have done much to unify electrical practice internationally, such as the International Standard of Resistance for Copper. The IEC also co-operates with other international bodies, particularly the International Union of Pure and Applied Physics and the International Bureau of Weights and Measures, in standardizing electrical units. These are of the greatest fundamental importance as they provide an electrical language, so to speak, which is universal. The principal basic electrical units had been established, prior to formation of the IEC through the International Electrical Congress.

Other Standards deal with specific subjects, such as the IEC Specification for Electrical Machinery, covering both rotating machines and transformers, which comprise the scopes of two ASA projects. Such IEC Standards are general and engineering in character, corresponding approximately in contents to the AIEE Standards on these subjects as they existed some 20 years ago.

Since the AIEE Standards existed prior to other electrical standards, they served as a basis for much of the early IEC work—hence the close agreement which existed between IEC recommendations and AIEE Standards. As standardization becomes more detailed, it is increasingly difficult to maintain this agreement. Considering the difficulty with which agreement is sometimes reached on standards in a single country in resolving different opinions in the industry, one can appreciate that standardization between countries is more tedious and must of necessity be confined more closely to fundamental requirements.

Although in international trade electrical equipment is sometimes specified to be in accordance with IEC recommendations, probably the most good has been accomplished by drawing together the standards of the various countries.

The publications of the IEC in the past have variously

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been known as Standards, Specifications, Rules, and so forth, but lately the IEC has agreed to call them Recommendations. An understanding has been reached in the Commission as to the status and extent these Recommendations are binding on the national committees of the various countries. In brief it is that:

"The formal decisions or agreements of the IEC on technical matters . . . express as nearly as possible an international consensus of opinion on the subjects dealt with. They have the force of recommendations for international use and they are accepted by the national committees in that sense. The desirability is recognized of extending international accord on these matters through an endeavor to harmonize national standardization rules and these recommendations in so far as national conditions will permit. The national committees pledge their influence toward that end."

The work of the IEC is subdivided among about 30 advisory committees. It has been customary to have a general get-together, called a plenary meeting, of all of these advisory committees about once every three years, but hardly a year passes, except for the war periods, when there has not been a meeting of some of the advisory committees.

The International Standards Association is a federation of 20 national standardizing bodies, each of which is the central clearing house for industrial standardization work in its own country. The purpose of the ISA is the systematic exchange of information on standardization work accomplished or in course of development in the different countries, and the promotion of uniformity among the various national standards, wherever this appears to be feasible and desirable.

The basis for the ISA was laid at an international conference held in New York, N. Y., in 1926. The ASA joined the ISA in the fall of 1929. The central office of the ISA is located in Basle, Switzerland.

Because of the war, ISA activities have ceased and the small headquarters staff has been dissolved. Records have been transferred to the Swiss national standardizing body for safekeeping.

The project work of the ISA is done by technical committees on which each member country has the right to be represented. The final report of a technical committee serves as a recommendation to all countries in establishing their national standards. Acceptance of such a recommendation is entirely voluntary.

Although the name of this association implies an all-inclusive scope, it has dealt mainly with mechanical subjects. However, it has on its slate a few subjects, such as acoustics, petroleum, paper sizes, and photography. None of its projects overlaps IEC work although some of the subjects, such as center heights of shafts, shaft extensions, shaft couplings, and pulleys, would be applicable to electric machines.

Safety Engineering in the Technical College

A. NAETER
MEMBER AIEE

On the theory that employers look with favor upon prospective employees who list among their qualifications training in safety engineering, The Oklahoma Agricultural and Mechanical College has been conducting a successful course in this field for several years.

ONE of the few courses in safety-engineering given in the United States is that which the Oklahoma Agricultural and Mechanical College has offered for some years past. Over ten years ago Colonel Philip S. Donnell, dean of engineering, now overseas on active military duty, appointed an engineering-faculty committee on first aid to study the problem of suitable instruction for graduating seniors in all departments of engineering. As a result, a required course of instruction in first aid was introduced in 1932 for all senior engineering students. Since so many engineering graduates regularly entered the oil industry, one of the major mining industries, the United States Bureau of Mines instructed their senior first-aid instructor at the Bureau of Mines station in McAlester to give the work.

This work consisted of five three-hour periods of instruction, covering such topics as the need of first-aid instruction, bleeding and pressure points, fractures and splinting, bandaging, heatstroke and sunstroke treatment. Particular emphasis was placed on the Schaeffer prone-pressure method of artificial respiration. Immediately favorable response came from practically all of the students. They were aware of the fact that the instructor had the saving of over 200 lives to his credit and, hence, could speak with authority. The work was offered to groups of 30 or 40 students.

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The author acknowledges the assistance of E. R. Stapley, acting dean; H. G. Thuesen, acting assistant dean; DeWitt Hunt, campus-safety-committee chairman; H. W. Orr, physiology professor; Fire Chief Pence; and J. B. Hynal of the United States Bureau of Mines, first-aid instructor.

Essential substance of a conference paper presented at the AIEE South West District technical meeting, Kansas City, Mo., April 28–30, 1943, and at the AIEE summer technical meeting, Cleveland, Ohio, June 21–25, 1943.

This course of instruction was given and still is being given during each spring semester. During the periods of instruction, this work takes precedence over all conflicting laboratory work.

Students are encouraged to notify their college engineering departments after leaving school when they have the opportunities to give first-aid treatment. During the first four years, at least four cases of life saving through artificial respiration were reported. Numerous cases of splinting and bandaging fractures, stopping bleeding, and the like have come to the attention of various representatives of the college.

After a few years of offering only first-aid instruction, it was felt that the time had come for safety-engineering instruction. Once a man had had a tourniquet on his arm, he would be aware much more acutely of the great desirability of avoiding the need of so drastic a treatment. That feeling would lead naturally into the field of accident prevention.

In 1936 a one-semester-credit course of instruction required for graduating seniors was introduced. The course, as outlined, consisted of three parts:

(*a*). Physiology and industrial hygiene, six or seven lectures given by a biologist speaking from the industrial angle.

(*b*). Safety-engineering and accident prevention work, five or six lectures on methods used in the fields of safety engineering, as practiced in industry.

(*c*). First aid, given by either a Bureau of Mines representative or a representative of the Red Cross.

During past years the physiology and industrial hygiene lectures have been given by a professor of physiology on the college faculty. These lectures deal with such topics as the structure of bones and joints, the blood, the heart, the lymphatic system. The discussion of the blood, for example, deals with its characteristics, blood plasma, coagulation, and the conditions necessary for it. The instructor is very successful in using engineering illustrations rather frequently. His comparisons between the lymphatic system of the body and the sanitary system of a city are interesting. At various times these lectures are supplemented by suitable motion pictures.

The safety-engineering portion of the course has varied, depending on the availability of suitable speakers. At different times the Petroleum Safety Council in Tulsa has arranged lecture series covering suitable topics presented by experienced safety engineers and others. In the spring of 1937 this series contained lectures on these topics:

1. Why Compensation Laws and Accident Prevention are Necessary.
2. The Supervisor's Responsibility.
3. Explosion Hazards.
4. Engineering Standards.
5. Explosives—Their Safe Use.
6. Transportation Problems.
7. Accident Analysis and Remedial Measures.

The series given in the fall of 1937 contained a new topic under the title, "Fire-Prevention Engineering." In March 1943, a major company sent its first-aid specialist to speak to the class. He brought along the company ambulance and much illustrative material. At times demonstration lectures are given by representatives of first-aid supply companies.

A lecture on the safe operation of motor vehicles was introduced as follows: "I believe, in order to obtain co-operation in safe operation of motor vehicles on our streets and highways, we must first give the people a picture of our present motor-vehicle problem, its development, the terrible annual toll it is exacting, and an intelligent, practical, well-planned program of adequate control based on years of experience, study, and research by traffic experts throughout the country. It should then be comparatively easy for intelligent sane operators of motor vehicles to realize how important it is, for their own protection as well as the lives and property of others." After analyzing the problem and the contributing causes, the solution was discussed under the headings of education of school and adult groups, engineering as applied to standardization and to building safety into streets and highways, and definite, practical, and reasonable policies of enforcement.

Since the AIEE is interested particularly in electrical problems, attention should be called to a talk dealing with practical safety methods applied to line construction. Proper job planning reduces the chance of accident and expedites the work. The choice and placement of men depends on physical fitness, experience, and mental ability and alertness. Emphasis must be placed on the proper selection, inspection, and maintenance of hand tools and mechanical equipment. The proper supervision of the employees involves safety instructions, use of bulletin boards, and follow-up by foreman and subforeman.

CAMPUS SAFETY-CONSCIOUS

Very definite efforts are being made continuously to make and keep the students and faculty safety-conscious. A campus safety committee, with a majority representation from the engineering faculty, is very active. Particular attention is paid to traffic hazards. A heavy traffic highway has been rerouted to miss the campus by over one half of a mile. Policemen are on duty at key street intersections when classes change. Since troop units have come to the college for instruction, some of the heavy traffic streets on the campus have been closed permanently and others declared military highways.

The campus safety committee has been unusually successful in keeping accidents at a very low level in shop and laboratory. It makes extensive use of National Safety Council posters and other similar material.

Laboratory and other campus facilities are subject to inspection upon request, as well as at unannounced intervals, by the Oklahoma Bureau of Factory Inspec-

tion–Accident Prevention. Its recommendations and requirements must be carried out within specified time intervals, and more serious hazards are eliminated immediately, even though doing so should involve shutting down a place where students or faculty or campus employees work.

One of the Stillwater fire stations is located on the campus. It serves both as a fire station for the campus and a part of town, as well as a laboratory for the only collegiate firemanship training school in the United States. It pays particular attention to matters involving fires and their dangers in town and on the campus.

CONCLUSION

These various safety elements have been listed to indicate a setting into which safety-engineering instruction fits very well. This work has been carried on for a time sufficiently long to put it well beyond the experimental stage.

In the time between the first World War and the present global war, increasing emphasis was placed on the importance of safety engineering in all of its ramifications. The requirements of the present war have brought it to the very forefront.

From the very beginning of the program it was recognized that employers look with favor upon prospective employees who list among their qualifications training in the basic elements of safety engineering as well as the possession of a first-aid certificate.

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The Horsepower Meter for Aircraft

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The torquemeter method of operating aircraft engines was developed to meet the need for more accurate engine control and to help ease the work of the pilot. The horsepower meter described herein was developed to provide suitable and accurate instrumentation for that method.

THE EVER INCREASING magnitudes of engine-horsepower ratings and the accompanying augmented fuel consumption has thrown the spotlight on improved methods of aircraft-engine operation. The existing method of "chart-horsepower" operation has been analyzed and found basically too inaccurate to warrant further refinement of the associated instrumentation. The development of the torquemeter-equipped engine bears witness to the need for more accurate engine control.

Airplane-engine control may be simplified by the use of a direct-reading brake-horsepower meter. Furthermore, the technique of the brake-horsepower meter, as described in this article, in combining electrically the torque output with engine speed, makes possible an increase in the accuracy of the instrumentation. With a suitable direct-reading brake-horsepower meter, it would be necessary only for the pilot to set the horsepower and revolutions per minute, and lean the engine gasoline–air mixture to the minimum allowable. No empirical "charts" would have to be consulted nor corrections for altitude and temperature made. Furthermore, inasmuch as the horsepower being measured is that actually delivered by the engine, all the incalculable factors affecting engine horsepower are no longer of any consequence to the pilot, who is interested solely in the power being developed at the propeller. The elimination of the tachometer reading, with its one per cent error, is realized. This is particularly true of the horsepower meter in conjunction with a-c tachometer installations of the frequency type (see Figure 2).

The basic circuit necessary to combine electrically the torque output of an engine with the engine speed in order to calculate brake horsepower is broadly old, patents having been issued for horsepower circuits prior to the beginning of the present century. The circuit in Figure 1 shows how the fundamental electrical equation, $I = E/R$, is adapted to an aircraft engine installation.

The pressure from the torquemeter of the engine varies a resistance inversely with the pressure, this resistance being connected in series with the engine tachometer generator and an ammeter which is calibrated to read in units of brake horsepower. This combination is electrically sound, but its practicability is limited from a maintenance standpoint because the variable resistance,

J. C. Luttrell is with the Army Air Force Transport Command, Washington, D. C., and W. A. Petrasek is project engineer, American Airlines, Inc., La Guardia Airport, New York, N. Y.

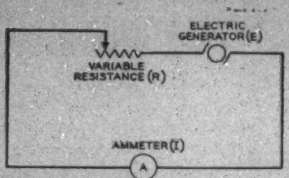

Figure 1. D-c horsepower-meter circuit

Brake-horsepower equation for engines with torquemeter attachments:

$$\frac{\text{Torque pressure} \times \text{rpm}}{\text{Constant}} = \text{brake horsepower} \qquad (1)$$

Equation for the electric circuit shown:

$$I = \frac{E}{R} \qquad (2)$$

In this circuit, E is directly proportional to rpm, R varies inversely with the torque pressure. Therefore,

$$E \sim \text{rpm and } R \sim \frac{1}{\text{torque pressure}} \qquad (3)$$

Substitute relationships (3) in (2):

$$I = \frac{E}{R} = \frac{\text{rpm}}{\frac{1}{\text{torque pressure}}} = \frac{\text{rpm} \times \text{torque pressure}}{1 \text{ (or } K)}$$

$$\text{Therefore } I = \frac{\text{rpm} \times \text{torque pressure}}{K} = \text{brake horsepower} \qquad (4)$$

tachometer generator, and ammeter have to be calibrated as a unit, making it impossible to change any one of the units on an airplane in a field without affecting the accuracy of the meter. The limitations of this type of horsepower meter may be compared with the limitations of the d-c tachometer installation which depends upon the voltage stability of a magneto for its accuracy.

The preferred a-c brake-horsepower meter is shown in Figure 2. A typical two- or three-phase a-c tachometer is installed. The output of any two of the existing tachometer-generator wires is connected across the terminals of a saturated-core transformer. The output of the transformer is applied to the fixed whole resistance of a potentiometer, the movable contact of which is controlled by engine torque. This potentiometer-control device is preferably of the type which develops torque right up to the control point.

The operation of the meter is as follows: The output frequency of the tachometer generator varies proportionately with engine speed. This proportional variation of frequency is transformed into a proportional voltage variation with speed by the saturated-core transformer which is relatively undisturbed by small changes in generator output voltage. This fact alone makes it possible to replace tachometer generators without having to recalibrate the horsepower meter, and permits the interchangeable use of various existing tachometer generators. The voltage variation which is proportional to engine speed is impressed across a potentiometer resistance, and a specific ratio of this voltage is impressed across an a-c voltmeter suitably calibrated in brake horsepower. This voltage ratio is determined by an electric motor-driven control unit which varies the potentiometer output resistance proportionately to engine torque. The resultant voltage measured on the indicator is proportional to both the potentiometer input-voltage variation as well as to the variation of the resistance ratio, and, hence, it is proportional to their product or brake horsepower. The wires shown by dotted lines in Figure 2 may be omitted in the installation provided the equipment is appropriately grounded as shown. It is seen that only one additional wire from the engine to the instrument panel is necessary for the installation of a brake-horsepower-meter indicator. The electric power leads for the torque-motor unit may be obtained from any convenient source of power in the engine nacelle, and will, at most, require only a short length of wire.

An analysis of the possible accuracy of the foregoing combination indicates that an over-all maximum error of approximately three per cent is feasible. No error is incurred in the engine-speed conversion to frequency. An error of 0.5 per cent can be maintained in the conversion from frequency to voltage in the saturated-core transformer. An error of 1.5 per cent can be allocated to the torque-varied potentiometer, and the indicator voltmeter limited to an error of one per cent. The total error is considered tolerable in view of the fact that the scale calibration of a standard aircraft indicator, having a 270-degree pointer movement, will not permit the reading of the instrument beyond an accuracy greater than three per cent.

The following is a summary of some of the more important advantages of the horsepower meter as described in this article:

1. It makes increased accuracy of engine control possible. Horsepower determination within three per cent is possible.
2. It provides a continuous check on engine operation, and makes possible the detection of leaky valves and ignition trouble through the reflection of a loss in engine-horsepower output.
3. It provides an immediate confirmation of takeoff power under all conditions of operation.
4. It provides a simple means of instrumentation for torquemeter operation of engines in the light of existing instrument limitations.

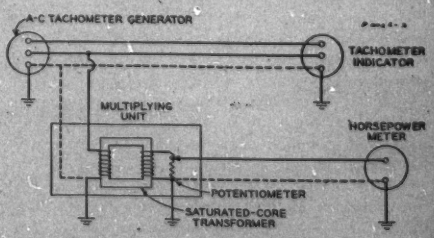

Figure 2. A-c horsepower-meter circuit

INSTITUTE ACTIVITIES

AIEE Officers to Be Nominated for 1944 Election

For the nomination of national officers to be voted upon in the spring of 1944, the AIEE national nominating committee will meet during the winter technical meeting, New York, N. Y., January 24–28, 1944. The officers to be elected are: a president, a national treasurer, three directors, and five vice-presidents, one from each of the odd-numbered geographical Districts. Fellows only are eligible for the office of president, and Members and Fellows for the offices of vice-president, director, and national treasurer.

To guide this committee in performing its constituted task, suggestions from the membership are, of course, highly desirable. To be available for the consideration of the committee, all such suggestions must be received by the secretary of the committee at Institute headquarters, not later than December 15, 1943.

In accordance with the provisions in the constitution and bylaws, as amended during 1935 and quoted in the following paragraphs, actions relative to the organization of the national nominating committee are now under way.

Constitution

28. There shall be constituted each year a national nominating committee consisting of one representative of each geographical District, elected by its executive committee, and other members chosen by and from the board of directors not exceeding in number the number of geographical Districts; all to be selected when and as provided in the bylaws. The national secretary of the Institute shall be the secretary of the national nominating committee, without voting power.

29. The executive committee of each geographical District shall act as a nominating committee of the candidate for election as vice-president of that District, or for filling a vacancy in such office for an unexpired term, whenever a vacancy occurs.

30. The national nominating committee shall receive such suggestions and proposals as any member or group of members may desire to offer, such suggestions being sent to the secretary of the committee.

The national nominating committee shall name on or before January 31 of each year, one or more candidates for president, national treasurer, and the proper number of directors, and shall include in its ticket such candidates for vice-presidents as have been named by the nominating committees of the respective geographical Districts, if received by the national nominating committee when and as provided in the bylaws; otherwise the national nominating committee shall nominate one or more candidates for vice-president(s) from the District(s) concerned.

Bylaws

SEC. 22. During September of each year, the secretary of the national nominating committee shall notify the chairman of the executive committee of each geographical District that by December 15 of that year the executive committee of each district must select a member of that District to serve as a member of the national nominating committee, and shall by December 15, notify the secretary of the national nominating committee of the name of the member selected.

During September of each year, the secretary of the national nominating committee shall notify the chairman of the executive committee of each geographical district in which there is or will be during the year a vacancy in the office of vice-president, that by December 15 of that year a nomination for a vice-president from that District, made by the District executive committee, must be in the hands of the secretary of the national nominating committee.

Between October 1 and December 15 of each year, the board of directors shall choose 5 of its members to serve on the national nominating committee and shall notify the secretary of that committee of the names so selected, and shall also notify the 5 members selected.

The secretary of the national nominating committee shall give the 15 members so selected not less than 10 days' notice of the first meeting of the committee, which shall be held not later than January 31. At this meeting, the committee shall elect a chairman and shall proceed to make up a ticket of nominees for the offices to be filled at the next election. All suggestions to be considered by the national nominating committee must be received by the secretary of the committee by December 15. The nominations as made by the national nominating committee shall be published in the March issue of *Electrical Engineering* (Journal of AIEE), or otherwise mailed to the Institute membership not later than the first week in March.

INDEPENDENT NOMINATIONS

Independent nominations may be made in accordance with provisions in article VI, section 31, of the constitution and section 23 of the bylaws, which are quoted below:

Constitution

31. Independent nominations may be made by a petition of twenty-five (25) or more members sent to the national secretary when and as provided in the bylaws; such petitions for the nomination of vice-presidents shall be signed only by members within the District concerned.

Bylaws

SEC. 23. Petitions proposing the names of candidates as independent nominations for the various offices to be filled at the ensuing election, in accordance with article VI, section 31 (constitution), must be received by the secretary of the national nominating committee not later than March 25 of each year, to be placed before that committee for the inclusion in the ballot of such candidates as are eligible.

On the ballot prepared by the national nominating committee in accordance with article VI of the constitution and sent by the national secretary to all qualified voters during the first week in April of each year, the names of the candidates shall be grouped alphabetically under the name of the office for which each is a candidate.

(*Signed*) H. H. HENLINE,
National Secretary

November 1, 1943

Future AIEE Meetings

Southern District Meeting
Roanoke, Va., November 16–18, 1943

Winter Technical Meeting
New York, N. Y., January 24–28, 1944

North Eastern District Meeting
Boston, Mass., April 1944

Summer Technical Meeting
St. Louis, Mo., June 26–30, 1944

North Eastern District Executive Committee Meets

The executive committee of the North Eastern District held its fall meeting in Schenectady, N. Y., October 8, 1943, with 100 per cent representation of Sections.

The meeting was addressed by W. F. Cotter (M '28), District vice-chairman of the AIEE committee on membership, who spoke on the activities of that committee and mentioned a plan to send a letter to each Section outlining the work expected of it in improving or sustaining membership. The general discussion following his talk brought out specific practices of the Sections represented. The Boston Section, which has as chairman of its membership committee one experienced in its work, endeavors to have a representative wherever there are four or more engineers. This Section also noted that changing its meeting place to one easy of access by public transportation improved attendance. Advance planning of the year's meetings is employed by several Sections as a means of attracting and sustaining membership. Publicity and membership activity is combined by the Rochester Section.

In this connection H. H. Henline (F '43) national secretary, speaking on Institute activities in general, stated that many Sections were experimenting with both geographic and technical subsections. The experience of the New York Section seems to indicate that attendance at the technical meetings overshadows that at the general-subject type.

The Connecticut Section has substituted a plan of shifting meeting locations for the alternative of forming subsections. Returning to the subject of meeting topics, the discussion considered orienting of meeting topics toward the war effort. The general opinion was that experience with the recent series on conservation of materials had been disappointing in attendance and interest. Rather than have the Institute headquarters provide speakers on specific subjects, most of the speakers preferred that it continue the list of successful meeting topics. Two Sections announced plans for talks on postwar planning, emphasizing personnel, changes in production, and consequent changes in loads on utilities.

Student Branch activities were discussed by R. G. Porter (M '35), chairman of the District committee on student activities. Despite the fact that wartime conditions have prevented student conventions at District technical meetings, he recommended holding a conference of Branch counselors and chairmen. It was voted to call such a meeting at the 1944 technical meeting. In addition, it was suggested that Professor Porter write to all Branches to stimulate combined activity

of Army and Navy trainees and civilian Branch members.

Other business of the meeting included the voting of a transfer of $500 from the treasury to an interest-bearing Government bond. A report on the Pittsfield District technical meeting was submitted by J. R. Meador (M '40) chairman of the Pittsfield Section (see *Electrical Engineering*, May 1943, pages 216–18). It was voted to accept the invitation of the Boston Section to the District to hold its 1944 technical meeting there in April. In addition Mr. Henline announced that the board of directors is ready to consider invitations for 1945 meeting locations, and the Niagara Frontier Section invited the 1945 District meeting to its territory.

The following appointments were made:

District co-ordinating committee—K. B. McEachron, V. Siegfried, R. G. Porter, M. H. Pratt, H. P. Turner, J. R. Meador, E. C. Brown.

Technical meeting committee—the foregoing seven men plus additional appointees who will be announced later.

Committee on award for best and initial paper prizes—A. G. Conrad, R. W. Ager, F. R. Longley.

C. F. Kettering

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H. S. Warren

PERSONAL • • • •

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J. B. MacNeill (A '18, F '42) manager of engineering, switchgear division, engineering department, Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa., has been appointed chairman of the AIEE committee on protective devices for 1943–44. Mr. MacNeill served on the committee for 1920–22, again from 1928 to 1932, and recently since 1936. He was born June 21, 1888, in Summerside, P. E. I., and was graduated from the Massachusetts Institute of Technology in 1913 with the degree of bachelor of science in electrical engineering. In 1913 Mr. MacNeill entered the employ of the Westinghouse company as a design engineer in the switchboard department. From 1918 to 1928 he was engineer in charge of the circuit-breaker design section. He was made manager of the circuit-breaker design department in 1931 and general manager of the distribution engineering department in 1933. He was transferred to Boston, Mass., as manager of the New England engineering department in 1933 but returned to East Pittsburgh in 1935 as manager of engineering. Under Mr. MacNeill's supervision 1,500,000-kva indoor powerhouse circuit breakers were developed, and the commercial application of the deion principle was accomplished. Several patents have been issued in his name. A member of the National Electrical Manufacturers Association, he represented that body at the World Power Conference in Berlin, Germany, in 1930. He also served on the AIEE committee on power transmission and distribution from 1933 to 1935.

H. S. Warren (A '03, F '13) consulting electrical engineer, New York, N. Y., has been appointed chairman of the AIEE board of examiners for 1943–44. He has been a member of the board since 1930. Mr. Warren was born in Oldtown, Me., March 3, 1873, and was graduated from Stanford University with the degree of bachelor of arts in 1898. After a year spent in wiring and installation work in the power plants of the Standard Electric Company of California, San Francisco; the California State Board of Harbor Commissioners; and the Nevada County Electric Power Company, Nevada City, Calif.; he joined the American Bell Telephone Company, Boston, Mass., in 1899. Occupied thereafter with telephone transmission developments, he designed the loading coils required for the successful commercial application of open-wire circuits about 1901. Later he designed the coil which permitted the widespread practical operation of phantom circuits. From 1909 to 1919 he was engaged in external relations for the American Telephone company in connection with railroad electrification. In 1919 he became protection development engineer, and after the research department of the American Telephone company was combined with the Bell Telephone Laboratories, Inc., New York, N. Y., in 1933, he was made director of protection development at the laboratories. In 1938 he retired from Bell Laboratories to open his own consulting practice. His Institute committee memberships include: safety codes, 1915–40 (chairman

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John Grotzinger (A '24) chief engineer, electrical engineering department, Goodyear Tire and Rubber Company, Akron, Ohio, has been appointed chairman of the AIEE committee on industrial power applications for 1943–44. Mr. Grotzinger has been a member of the committee since 1939 and was a member of the predecessor committee on general power applications from 1930 to 1934. Born in Schaffhausen, Switzerland, December 22, 1891, he was graduated from Bienne Institute of Technology in Switzerland in 1913. During 1913 he was draftsman for the Canadian Crocker-Wheeler Company, St. Catharines, Ont., and electrician for the Toronto Power Company and the American Cyanamid Company, both of Niagara Falls, Ont. From 1914 to 1917 he was assistant works engineer and works engineer for Electro Metals Ltd., Welland, Ont. He was employed first as engineer in charge of design of plants and then as superintendent of operations by the Pacific Electro Metals Company, San Francisco, Calif., during 1917 and 1918. In 1919 he worked as electrical engineer for the McKinnon Dash Company, Buffalo, N. Y., and in 1920 he joined the Goodyear Tire and Rubber Company as electrical engineer. In 1927 he was appointed chief electrical engineer. In this position he has designed many rubber plant projects both in the United States and abroad. World War II has brought aircraft plants, ordnance plants, and synthetic rubber plants within the scope of his work.

H. E. Wulfing (M '23) system development engineer, Commonwealth Edison Company, Chicago, Ill., has been appointed to the chairmanship of the 1943–44 AIEE committee on power transmission and distribution of which he has been a member since 1936. Born August 20, 1881, in Richland Center, Wis., he received the degree of bachelor of science in electrical engineering from the University of Wisconsin in 1905. Mr. Wulfing commenced his engineering career as a wireman for the Chicago, Rock Island, and Pacific Railroad, Chicago, Ill., in 1905. From 1906 to 1908 he was construction foreman for W. E. Clow and Company, Newcomerstown, Ohio. In 1908 he became testing engineer with the Westinghouse Electric and Manufacturing Company, Pittsburgh, Pa., and during 1909 and 1910 he worked as appraisal engineer for H. M. Byllesby and Company, Chicago. Joining the Commonwealth Edison Company as superintendent of the outside plant department in 1910, he was transferred to the inside plant division in 1913. Remaining in that division until 1924, he served as engineer of substations and assistant superintendent of overhead lines. In 1924 he was named staff engineer attached to the office of the chief electrical engineer, and in 1933 he became system development engineer. He served on the AIEE committee on power generation for 1936–37 and is currently serving on the committee on award of Institute prizes.

W. N. Zippler (A '20, M '38) chief electrical engineer, Gibbs and Cox, Inc., New York, N. Y., has been appointed chairman of the 1943–44 AIEE committee on marine transportation. He has been a member of this committee and its predecessors since 1929. Mr. Zippler was born March 19, 1896, in Philadelphia, Pa., and received the degrees of bachelor of science in 1920 and electrical engineer in 1932 from the University of Pennsylvania. In 1920 he joined the staff of the construction department of the International Mercantile Marine Company, New York. He remained in this position when the construction department was incorporated as Gibbs Brothers in 1922, and that firm was enlarged to Gibbs and Cox in 1929. In 1940 Mr. Zippler was appointed chief electrical engineer. He has supervised the design and construction of the electrical installation, including electrical propulsion, for many large passenger and cargo vessels, as well as for United States Naval destroyers and for private yachts. He served as electrical consultant in the preparation of *United States Senate Report 184*, which established a safety standard for construction of American passenger vessels after the Morro Castle disaster. In 1939 he acted as alternate for the AIEE representative on the American Standards Association's sectional committee on electrical installations on shipboard. Mr. Zippler is a member of the Society of Naval Architects and Marine Engineers and of Eta Kappa Nu.

G. W. Bower (A '18, M '40) engineer, Public Service Electric and Gas Company, Newark, N. J., has been appointed 1943–44 chairman of the AIEE Sections committee. Mr. Bower was born in Philadelphia, Pa., February 22, 1894, and was graduated from Drexel Institute in 1914. He commenced his career with the Public Service company in Camden, N. J., in 1914 as draftsman and in 1917 advanced to district chief clerk. After service with the United States Army he returned to the Public Service company in 1919 and became district foreman and assistant district line foreman. He was appointed local field engineer in 1924 and district superintendent in 1927. In 1943 he was made engineer in the general office of the company. Mr. Bower is a past chairman (1942–43) of the AIEE Philadelphia Section and has served as chairman of several committees of the Philadelphia Section. He has served on the national membership committee for the past year and is currently serving on the committee on planning and co-ordination of Institute activities.

R. H. Hughes (A '20, F '41) vice-president and general manager of the Manhattan, Bronx, and Westchester area of the American Telephone and Telegraph Company has been appointed staff vice-president of the company. Mr. Hughes entered the employ of the New York Telephone Com-

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1935–37); traction and transportation, 1916–17; power transmission and distribution, 1925–41; as well as the electrical committee of the National Fire Protection Association on which he represented the Institute 1935–37, and acted as alternate for 1923–24, and for 1938–43. In 1931 he shared in the national prize award for the best paper in engineering practice for his contribution, "Status of Joint Development and Research on Low-Frequency Induction," to the symposium on co-ordination of power and telephone plant. He is a fellow of the American Association for the Advancement of Science, a member of Sigma Xi, and a past president of the Telephone Society of New England.

John Grotzinger (A '24) chief engineer, electrical engineering department, Goodyear Tire and Rubber Company, Akron, Ohio, has been appointed chairman of the AIEE committee on industrial power applications for 1943–44. Mr. Grotzinger has been a member of the committee since 1939 and was a member of the predecessor committee on general power applications from 1930 to 1934. Born in Schaffhausen, Switzerland, December 22, 1891, he was graduated from Bienne Institute of Technology in Switzerland in 1913. During 1913 he was draftsman for the Canadian Crocker-Wheeler Company, St. Catharines, Ont., and electrician for the Toronto Power Company and the American Cyanamid Company, both of Niagara Falls, Ont. From 1914 to 1917 he was assistant works engineer and works engineer for Electro Metals Ltd., Welland, Ont. He was employed first as engineer in charge of design of plants and then as superintendent of operations by the Pacific Electro Metals Company, San Francisco, Calif., during 1917 and 1918. In 1919 he worked as electrical engineer for the McKinnon Dash Company, Buffalo, N. Y., and in 1920 he joined the Goodyear Tire and Rubber Company as electrical engineer. In 1927 he was appointed chief electrical engineer. In this position he has designed many rubber plant projects both in the United States and abroad. World War II has brought aircraft plants, ordnance plants, and synthetic rubber plants within the scope of his work.

H. E. Wulfing (M '23) system development engineer, Commonwealth Edison Company, Chicago, Ill., has been appointed to the chairmanship of the 1943–44 AIEE committee on power transmission and distribution of which he has been a member since 1936. Born August 20, 1881, in Richland Center, Wis., he received the degree of bachelor of science in electrical engineering from the University of Wisconsin in 1905. Mr. Wulfing commenced his engineering career as a wireman for the Chicago, Rock Island, and Pacific Railroad, Chicago, Ill., in 1905. From 1906 to 1908 he was construction foreman for W. E. Clow and Company, Newcomerstown, Ohio. In 1908 he became testing engineer with the Westinghouse Electric and Manufacturing Company, Pittsburgh, Pa., and during 1909 and 1910 he worked as appraisal engineer for H. M. Byllesby and Company, Chicago. Joining the Commonwealth Edison Company as superintendent of the outside plant department in 1910, he was transferred to the inside plant division in 1913. Remaining in that division until 1924, he served as engineer of substations and assistant superintendent of overhead lines. In 1924 he was named staff engineer attached to the office of the chief electrical engineer, and in 1933 he became system development engineer. He served on the AIEE committee on power generation for 1936–37 and is currently serving on the committee on award of Institute prizes.

W. N. Zippler (A '20, M '38) chief electrical engineer, Gibbs and Cox, Inc., New York, N. Y., has been appointed chairman of the 1943–44 AIEE committee on marine transportation. He has been a member of this committee and its predecessors since 1929. Mr. Zippler was born March 19, 1896, in Philadelphia, Pa., and received the degrees of bachelor of science in 1920 and electrical engineer in 1932 from the University of Pennsylvania. In 1920 he joined the staff of the construction department of the International Mercantile Marine Company, New York. He remained in this position when the construction department was incorporated as Gibbs Brothers in 1922, and that firm was enlarged to Gibbs and Cox in 1929. In 1940 Mr. Zippler was appointed chief electrical engineer. He has supervised the design and construction of the electrical installation, including electrical propulsion, for many large passenger and cargo vessels, as well as for United States Naval destroyers and for private yachts. He served as electrical consultant in the preparation of *United States Senate Report 184*, which established a safety standard for construction of American passenger vessels after the Morro Castle disaster. In 1939 he acted as alternate for the AIEE representative on the American Standards Association's sectional committee on electrical installations on shipboard. Mr. Zippler is a member of the Society of Naval Architects and Marine Engineers and of Eta Kappa Nu.

G. W. Bower (A '18, M '40) engineer, Public Service Electric and Gas Company, Newark, N. J., has been appointed 1943–44 chairman of the AIEE Sections committee. Mr. Bower was born in Philadelphia, Pa., February 22, 1894, and was graduated from Drexel Institute in 1914. He commenced his career with the Public Service company in Camden, N. J., in 1914 as draftsman and in 1917 advanced to district chief clerk. After service with the United States Army he returned to the Public Service company in 1919 and became district foreman and assistant district line foreman. He was appointed local field engineer in 1924 and district superintendent in 1927. In 1943 he was made engineer in the general office of the company. Mr. Bower is a past chairman (1942–43) of the AIEE Philadelphia Section and has served as chairman of several committees of the Philadelphia Section. He has served on the national membership committee for the past year and is currently serving on the committee on planning and co-ordination of Institute activities.

R. H. Hughes (A '20, F '41) vice-president and general manager of the Manhattan, Bronx, and Westchester area of the American Telephone and Telegraph Company has been appointed staff vice-president of the company. Mr. Hughes entered the employ of the New York Telephone Com-

H. E. Wulfing

John Grotzinger

G. W. Bower

W. N. Zippler

S. B. Ingram

F. A. Cowan

G. A. Waters

pany, New York, in 1914. He became local trunk engineer in 1925 and plant extension engineer in 1927. Later that year he was made assistant vice-president of the company. He was appointed vice-president and general manager of the Bronx and Westchester area in 1939 and in 1941 added management of the Manhattan area to his duties. **W. A. Kietzman** (M '23) vice-president and general manager, New York Telephone Company, Albany, succeeds Mr. Hughes. Mr. Kietzman first worked for the American Telephone company from 1912 to 1921, as student engineer, assistant engineer, exchange rate practice engineer, and cost engineer. He joined the Bell Telephone Company of Pennsylvania, Philadelphia, as general commercial engineer in 1921. Returning to the American Telephone company in 1927 he became sales and directory engineer. From 1929 to 1938 he was general commercial engineer for the New York Telephone Company, New York, and in 1939 he was transferred to Albany as vice-president and general manager. **R. F. Davis** (A '25) formerly head of the exchange and special services group, American Telephone company, has been made station engineer in the plant engineering division. He has been with the Telephone company since 1921. **J. A. Parrott** (M '37) engineer for the Telephone company will succeed Mr. Davis as head of the exchange and special services group in the operation and engineering department of the American Telephone company. He has been employed by the telephone company since 1920.

F. A. Cowan (M '29) transmission engineer, American Telephone and Telegraph Company, New York, N. Y., has been appointed chairman of the AIEE technical program committee and the committee on award of Institute prizes for 1943–44. Mr. Cowan has been a member of the technical program committee since 1941. Born in Escatawpa, Ala., August 30, 1898, he received the degree of bachelor of science in electrical engineering from the Georgia School of Technology in 1919. In 1920 he entered the employ of the American Telephone and Telegraph Company, Atlanta, Ga., and was transferred in 1922 to the company's long lines engineering department in New York where he engaged in engineering work on special services. He became a division transmission engineer in the long lines plant department in 1926 and in 1928 was made engineer of transmission of the long lines department. Since 1940 he has been transmission engineer. Mr. Cowan has been a member of the AIEE committee on communications since 1941 and has served in several positions in the New York Section. The holder of patents on a number of inventions, he is also the author of various technical papers and articles. Mr. Cowan is a member of the Institute of Radio Engineers and holds the commission of lieutenant commander in the United States Naval Reserve.

S. B. Ingram (M '38) electronics research engineer, Bell Telephone Laboratories, Inc., has been appointed 1943–44 chairman of the AIEE committee on electronics of which he has been a member since 1942. Born October 8, 1903, in Bottineau, County, N. D., Mr. Ingram received the bachelor of arts degree from the University of British Columbia in 1925 and the degree of doctor of philosophy from the California Institute of Technology in 1928. From 1928 to 1930 he engaged in experimental and theoretical research in the atomic spectra of the light elements as a fellow of the National Research Council at the University of Michigan. In 1930 he joined the technical staff of Bell Telephone Laboratories to take charge of work on gas-filled vacuum tubes and in 1936 was named vacuum-tube development engineer. In 1939 he become electronics research engineer. During the past year, Mr. Ingram has served on the AIEE committee on communication. He is a fellow of the American Physical Society and an associate of the Institute of Radio Engineers.

G. A. Waters (A '09, F '21) chief engineer, electrical division, engineering department, Wagner Electric Corporation, St. Louis, Mo., has been appointed chairman of the AIEE committee on code of principles of professional conduct for 1942–43. Mr. Waters was born December 1, 1883, in Cleveland, N. Y., and was graduated from Syracuse University with the degree of bachelor of science in electrical engineering in 1907. From 1907 to 1909 he was instructor in mathematics and drawing at Washington University, St. Louis. He joined the Wagner Electric company as transformer designer in 1909 and in 1916 became plant engineer. In 1918 he was made assistant chief engineer and in 1926 was appointed chief engineer. Mr. Waters has been a member of the AIEE committee on electrical machinery since 1936.

M. L. Manning (A '36, M '42) formerly associate professor of electrical engineering, Illinois Institute of Technology, Chicago, has been appointed associate professor of electrical engineering and supervisor of the new high-voltage research laboratory at Cornell University, Ithaca, N. Y. Professor Manning holds the degrees of bachelor of science from South Dakota State College (1927) and master of science from the University of Pittsburgh (1932). From 1932 to 1936 he was instructor in the mathematics department of the University of Pittsburgh (Pa.) He was supervisor of the high-voltage laboratories of the Westinghouse Electric and Manufacturing Company, Sharon, Pa., as well as Westinghouse lecturer in electrical engineering on the staff of the University of Pittsburgh, from 1937 to 1942. In 1942 he was appointed to the staff of the Illinois Institute of Technology. **M. M. Peterson** (A '29, M '42) formerly laboratory engineer, Westinghouse Electric and Manufacturing Company, Sharon, Pa., has been appointed assistant professor of high-voltage practice in the new high-voltage laboratory at Cornell University. A 1927 graduate of Ohio Northern University, Professor Peterson was first employed by the Westinghouse company in 1928. Since 1931 he has been engaged in high-voltage research work.

D. S. Jacobus (A '03) retired consulting engineer of the Babcock and Wilcox Company, New York, N. Y., has been awarded the Miller Medal of the American Welding Society for the most conspicuous contribution to research, standardization, and advancement of welded construction. Born in Ridgefield, N. J., January 20, 1862, he was graduated from Stevens Institute of Technology in 1884 and received the degree of doctor of engineering in 1906. As a member of the faculty of the department of experimental mechanics of Stevens Institute, Hoboken, N. J., he served as instructor and assistant professor from 1884 to 1894. In the latter year he was made professor. In 1906 he joined the Babcock and Wilcox Company as advisory engineer and head of the engineering department. He is a past president of the American Welding Society, the Society of Refrigerating Engineers, and the American Society of Mechanical Engineers, as well as a member of the Society of Naval Architects and Marine Engineers, the American Institute of Mining and Metallurgical Engineers, the American Mathematical Society, the Society for the Promotion of Engineering Education, the American Association for

the Advancement of Science, and the Holland Society of New York.

P. M. Downing (A '93, F '42) vice-president and general manager, Pacific Gas and Electric Company, San Francisco, Calif., has been appointed executive vice-president. Mr. Downing has been associated with the Pacific Gas company since 1901 when he became manager in charge of engineering, construction, and business development of its predecessor, the Colusa Gas and Electric Company. In turn he worked as division superintendent for the Bay Counties Power Company, San Francisco, and superintendent of operation for the California Gas and Electric Company, San Francisco, until all three companies merged to form the Pacific Gas and Electric Company in 1905. In 1908 he was given general supervision of the operation and maintenance of hydroelectric and steam generating stations, transmission-lines substations, and distribution systems for the new company. With supervision of engineering design added to his duties in 1917, he became chief engineer in the electric department. He was made vice-president in charge of electric construction and operation in 1929, and in 1941 was named vice-president and general manager. Mr. Downing was a vice-president of the Institute from 1925 to 1927.

R. L. Frisby (A '17, M '27) electrical engineer, power plants, Kansas City (Mo.) Light and Power Company, has retired. Mr. Frisby's first engineering work was substation operation and maintenance for the Commonwealth Edison Company, Chicago, Ill., from 1903 to 1905. In the latter year he became central-station testing engineer. Leaving the Commonwealth Edison Company in 1919, he entered the employ of the Kansas City Light and Power Company to take charge of the operation, maintenance construction, and engineering of all generating stations. Mr. Frisby is a past chairman of the AIEE Kansas City Section.

F. A. Decker (M '39) formerly assistant professor of engineering, Texas College of Mines and Metallurgy, El Paso, has been appointed associate professor of engineering at the University of New Mexico, Albuquerque. Professor Decker received the degrees of bachelor of science in 1927 and electrical engineer in 1932 from Kansas State College. He was instructor in electrical engineering at the University of Arizona from 1928 to 1933, before joining the faculty of the College of Mines and Metallurgy in 1935.

A. B. Campbell (A '20, F '38) formerly engineer on the staff of the Edison Electric Institute, New York, N. Y., has become representative for the Eastern States for Hughes Brothers, Seward, Neb. Mr. Campbell joined the engineering staff of the EEI in 1933 after the dissolution of the National Electric Light Association with which he had been connected since 1923. His work with both organizations was in the fields of codes and standards, transmission and distribution, and accident prevention.

A. D. Pettee (A' 20, M '37) formerly district sales engineer, General Cable Corporation, Chicago, Ill., has been made technical superintendent of the corporation's Bayonne, N. J., plant. Before joining the General Cable Corporation in 1929, he was associated with the firm of D. C. and W. B. Jackson (now Jackson and Moreland), Boston, Mass.; the International Harvester Company, Chicago; and the New York (N. Y.) Edison Company.

Alexander Kennedy, Jr. (A '10, M '43) application engineer, federal and marine department, General Electric Company, Schenectady, N. Y., has been made assistant to the manager of the department. For the past ten years Mr. Kennedy has been application engineer on main propulsion turbines and gears designed and manufactured for Navy combat vessels, as well as for the merchant marine. He is a member of the Society of Naval Architects and Marine Engineers.

E. H. Howell (A '42) formerly manager of the Toledo, Ohio, office of the General Electric Company has been appointed manager of the company's meter and instrument division. Mr. Howell entered the employ of the General Electric Company, Schenectady, N. Y., in 1922 as a student engineer. He has since held the positions of transformer tester, transformer specialist, and manager of the Memphis, Tenn., office.

J. A. Davis (A '30, M '40) formerly general superintendent, transportation department, El Paso (Tex.) Electric Company, has been appointed manager of the transportation department of the Virginia Electric and Power Company, Norfolk. A 1927 graduate of Virginia Polytechnic Institute, Mr. Davis previously was associated with the Virginia Electric and Power Company from 1927 to 1939.

C. E. Nichols (A '39) formerly engineer, Tennessee Valley Authority, Washington, D. C., is now in charge of the Washington office of the American Warehousemen's Association, merchandise division. Associated with TVA since 1937, Mr. Nichols was head civil engineer and steam-plant project engineer at Knoxville, Tenn., before his transfer to Washington in 1942.

H. P. Richmond (A '36) formerly district manager, Jersey Central Power and Light Company, Dover, has been appointed general superintendent of operations for the company. Mr. Richmond entered the employ of the company in 1929 as a cadet engineer. He has been district manager since 1936.

H. H. Weber (A '27, F '40) formerly electrical engineer, wire division, United States Rubber Company, New York, N. Y., has been appointed sales manager of the wire and cable department. A 1917 graduate of Lehigh University, Mr. Weber joined the sales department of the United States Rubber Company in 1934.

H. J. MacLeod (A '23, M '39) head of the mechanical- and electrical-engineering departments, University of British Columbia, Vancouver, was made an officer of the Order of the British Empire in the King's Birthday Honors List for "valuable public service in connection with scientific research."

C. O. Bickelhaupt (M '22, F '28) vice-president-on-leave, American Telephone and Telegraph Company, New York, N. Y., and a colonel in the United States Army has been appointed commanding officer of the eastern Signal Corps replacement training center, Fort Monmouth, N. J.

E. F. Peterson (A '33) formerly engineer in the vacuum-tube engineering department, General Electric Company, Schenectady, N. Y., has been placed in charge of design engineering of receiving tubes. He has been employed by the General Electric Company since 1934.

W. G. Knickerbocker (A '20, M '30) formerly assistant superintendent of meters, Detroit (Mich.) Edison Company, has been appointed superintendent of meters. An employee of the Edison company since 1919, he had been assistant superintendent since 1929.

J. H. Yarnall (M '19) formerly assistant superintendent of power, Boston (Mass.) Elevated Railway, has been appointed superintendent of power for the railway. He has been employed by the Boston railway since 1906 and was named assistant superintendent of power in March 1943.

G. H. Teommey, Jr. (A '27, M '33) formerly assistant engineer, Consolidated Edison Company of New York, Inc., has secured a wartime leave of absence to join the Sperry Gyroscope Company, Garden City, N. Y.

F. A. Wahlers (A '35) formerly division engineer, Consolidated Edison Company of New York (N. Y.), Inc., has been given a wartime leave of absence to join the Tennessee Eastman Corporation, Kingsport.

D. S. Wegg (A '08, M '20) formerly of the engineering department, American Writing Paper Corporation, Holyoke, Mass., is now an engineer with the firm of Jackson and Moreland, Boston, Mass.

OBITUARY

William Marcus Potts (A '36) chief electrician, Pacific Coast Borax Company, Boron, Calif., died June 16, 1943. He was born September 16, 1894, at Wynnewood, Okla., and was employed first as an electrician on mill and substation construc-

tion for the Bluestone Mining and Smelting Company, Mason, Nev., during 1919 and 1920. From 1920 to 1924 he worked as electrician on mine, mill, substation, and industrial-plant construction for the Pacific Gas and Electric Company, San Francisco, Calif.; the Standards Metals Company, Reno, Nev., the Moore Drydock Company, Oakland, Calif., and the Pan American Petroleum Company, Los Angeles, Calif. From 1924 to 1926 he held the position of chief electrician for the Pacific Coast Borax Company, Ryan, Calif. He did construction and maintenance work for the Bethlehem Shipbuilding Company, San Francisco, from 1926 to 1929. In 1929 he joined the May Automatic Oil Burner Company, Oakland, as electrician and salesman and in 1930 became a member of the firm, Frazier and Potts, Yerington, Nev. He returned to the Pacific Borax company in 1932 at Death Valley, Calif., becoming chief electrician at Hinkley, Calif., in 1933, and at Boron in 1938. He was a member of the American Institute of Mining and Metallurgical Engineers.

John E. Brobst (A '19) general consultant, industrial control engineering department, General Electric Company, Schenectady, N. Y., died September 30, 1943. He was born in Gilmanton, Wis., November 14, 1880, and was graduated from the University of Wisconsin with the degree of bachelor of science in electrical engineering in 1903. That year he was employed in the General Electric company's motor design department to work on design of d-c motors. After several years of special engineering assignments he was transferred, in 1916, to the industrial control department as assistant engineer. In 1920 he became designing engineer in that department. He was made works manager of the company's Bloomfield, N. J., plant in 1929 and in 1930 returned to Schenectady as managing engineer of the industrial control department. In 1943 he was appointed general consultant to the department. Mr. Brobst served on the AIEE committee on safety codes from 1927 to 1929 and is credited with several inventions related to motors and motor control.

Frederick Slocumb Freeman (A '16, M '28) superintendent of power, Boston (Mass.) Elevated Railway, died recently. He was born December 3, 1880, at Brookfield, Nova Scotia. After holding various positions connected with steam engineering, Mr. Freeman joined the Boston Railway in 1907 as mechanic and assistant chief engineer. In 1908 he was made chief engineer of the company's Dorchester power station and in 1911 of the South Boston power station. In 1913 he was appointed superintendent of power for the whole system which entailed responsibility for the operation and maintenance of all steam and power stations as well as supervision of construction of new projects.

James Percy Robinson (A '26) Pacific Coast manager, the Kerite Insulated Wire and Cable Company, Inc., San Francisco, Calif., died September 20, 1943. He was born August 14, 1887, in Washington, D. C. From 1906 to 1923 he worked as signal construction foreman, assistant supervisor of signal construction, and signal inspector for the Southern Pacific Railroad. In 1923 he joined the National Safety Appliance Company as signal engineer and in 1926 entered the employ of the Kerite Insulated Wire and Cable company as Pacific district representative. He was appointed manager of the district in 1940.

Theodore R. Cortright (A '43) engineer, C-O-Two Fire Equipment Company, Newark, N. J., died June 22, 1943. He was born August 19, 1919, at Berwick, Pa., and was graduated from Lehigh University with the degree of bachelor of science in electrical engineering in 1942. For six months following his graduation he was employed as junior engineer in the power drive department of the York (Pa.) Safe and Lock Company. In November 1942 he joined the C-O-Two Fire Equipment Company.

Otis C. Kirkman, Jr. (A '39) draftsman, Chattanooga (Tenn.) Electric Power Board, died May 21, 1943. Born in Cookerville, Tenn., December 7, 1916, he was graduated from the University of Tennessee with the degree of bachelor of science in electrical engineering in 1938. He had worked for the Electric Power Board since 1938 and was a member of Tau Beta Pi.

William John Wooldridge (A '06, F '38) retired manager of electrical sheet sales, Allegheny Ludlum Steel Corporation, Brackenridge, Pa., died April 6, 1943. He was a member of the AIEE committee on applications to iron and steel production for 1937–38. For an outline of Mr. Wooldridge's career see *Electrical Engineering*, August 1943, page 377.

MEMBERSHIP

Recommended for Transfer

The board of examiners, at its meetings on September 30 and October 21, 1943, recommended the following members for transfer to the grade of membership indicated. Any objections to these transfers should be filed at once with the national secretary.

To Grade of Fellow (September 30)

Miller, W. J., prof. and head, Dept. of Elec. Engg., University of Alabama, University, Ala.
Small, Alvah, president, Underwriters' Labs., Inc., Chicago, Ill.

2 to grade of Fellow

To Grade of Member (September 30)

Adams, C. C., chief engr., Quality Electric Co., Los Angeles, Calif.
Allinson, A. R., prof. and head of Dept. of Elec. Engg., Wayne University, Detroit, Mich.
Appleby, C. D., supt. of Municipal Utilities, Town of Middletown, Del.
Bell, J. S., development engr., Western Electric Co., Kearny, N. J.
Bliss, W. H., research engr., RCA Laboratories, Riverhead, N. Y.
Boyajian, J. A., chief engr., Metal Specialties Mfg. Co., Chicago, Ill.
Brown, E. C., acting mgr., Connecticut Valley Power Exchange, Hartford, Conn.
Brown, N. F., engr., accountant, Southern California Edison Co. Ltd., Los Angeles, Calif.
Cordray, R. E., charge of relay engg., General Electric Co., Philadelphia, Pa.
Daus, G. A., relay engr., Public Service Co. of Northern Illinois, Maywood, Ill.
Davis, E. W., group head, electrical, Standard Oil Development Co., Elizabeth, N. J.
Dynes, W. A., project engr., AAF Materiel Command, Wright Field, Dayton, Ohio.
Edgar, R. F., section head, General Engg. Lab., General Electric Co., Schenectady, N. Y.
Graves, H. C., elec. engr., ITE Circuit Breaker Co., Philadelphia, Pa.
Harries, W. H., associate elec. engr., Bonneville Power Administration, Portland, Oreg.
Herszler, E. A., associate prof., Pratt Institute, Brooklyn, N. Y.
Hornfeck, A. J., elec. research engr., Bailey Meter Co., Cleveland, Ohio.
Hutchings, J. H., chief engr., Continental Electric Co., Geneva, Ill.
Jayne, G. E., Dover, N. J.
Keck, J. N., elec. designer, James Stewart Co., Chicago, Ill.
Kirkland, J. F., asst. supt., Diesel Div., Baldwin Locomotive Works, Philadelphia, Pa.
Kirkwood, R. H., Major, A.U.S., New York.
Kopper, J. M., instructor in elec. engg., Johns Hopkins University, Baltimore, Md.
Lang, G. F., street lighting engr., Public Service Co. of Colorado, Denver, Colo.
Lewis, M. T., Port Signal Officer, U. S. Army, Fort Mason, Calif.
Limpus, L. M., supt. of Reclamation Dept., Oklahoma Gas & Electric Co., Oklahoma City, Okla.
Linke, H. M., chief operator, Spruce Falls Power & Paper Co. Ltd., Kapuskasing, Ont., Can.
Long, H. H., general engr., Knoxville Electric Power & Water Board, Knoxville, Tenn.
Long, R. P., General Plant Mgr., Bell Telephone Co. of Pa., Philadelphia, Pa.
Martin, L. D., senior electrical engr., U. S. Engineers, Atlanta, Ga.
Mayott, C. W., mgr., Connecticut Valley Power Exchange, Hartford, Conn.
Meyer, C. A., elec. design engr., Public Utility Engg. & Service Corp., Chicago, Ill.
Montgomery, W. E., chief load dispatcher, Basic Magnesium, Inc., Las Vegas, Nev.
Morton, P. L., asst. prof. of elec. engg., Univ. of California, Berkeley, Calif.
Oliver, T. S., underground engr., Public Service Co. of Colorado, Denver, Colo.
Pack, H. T., elec. supt., West Coast Shipbuilders, Ltd., Vancouver, B. C., Can.
Rader, L. T., elec. engr., General Electric Co., Schenectady, N. Y.
Reed, M. B., prof. of elec. engg., Illinois Institute of Technology, Chicago, Ill.
Rue, E. C., asst. supt., Trans. & Dist., Boston Edison Co., Boston, Mass.
Schmitt, G. E., chief engr., Lower Colorado River Authority, Austin, Tex.
Schulz, E. H., instructor in elec. engg., Illinois Institute of Technology, Chicago, Ill.
Shutt, C. C., mgr., Small Motor Div., Westinghouse Elec. & Mfg. Co., Lima, Ohio.
Stauder, L. F., associate prof. of elec. engg., Univ. of Notre Dame, Notre Dame, Ind.
Steede, J. H., asst. to chief engr., British Columbia Elec. Railway Co. Ltd., Vancouver, B. C., Can.
Thielman, J. A., senior engr., Philadelphia Electric Co., Philadelphia, Pa.
Umphrey, D. M., central station elec. engr., Westinghouse Electric & Mfg. Co., Wilkinsburg, Pa.
Vernam, G. S., senior engr., Postal Telegraph-Cable Co., New York.
Ward, R. T., in charge of Expediting of electrical Equipment, Aluminum Co. of Canada, Montreal, Can.
Watkins, D. L., product engr., American Steel & Wire Co., Worcester, Mass.

49 to grade of Member

To Grade of Fellow (October 21)

Buehner, R. O., elec. engr., American Steel & Wire Co., Cleveland, Ohio.
Hoeppner, H. L., elec. engr., Public Utility Engg. & Service Corp., Chicago, Ill.

2 to grade of Fellow

To Grade of Member (October 21)

Connery, A. F., chief engr., Postal Telegraph Cable Co., New York.
Day, J. H., engr., I.T.E. Circuit Breaker Co., Philadelphia, Pa.
Dempsey, W. A., Lieut., U. S. Naval Reserve, Washington, D. C.
Dryar, H. A., chief load dispatcher, Philadelphia Elec. Co., Philadelphia, Pa.

Emrick, A. N., mgr., Wagner Electric Corp., Dallas, Texas.
Figenzer, Theodore, elec. engr., J. Gordon Turnbull & Swerdrup & Parcel, St. Louis, Mo.
Fuge, H. B., elec. engr., Diehl Mfg. Co., Finderne Plant, Somerville, N. J.
Garman, C. W., sales and application engr., General Electric Co., Schenectady, N. Y.
Hilbert, E. H., methods engr., Ward Leonard Elec. Co., Mount Vernon, N. Y.
Jolliff, E. N., field service engineer, Crouse-Hinds Co., Houston, Texas.
Kofoid, M. J., research engr., Westinghouse Research Labs., East Pittsburgh, Pa.
McCall, C. C., system operator, Cleveland Electric Illuminating Co., Cleveland, Ohio.
Nason, H. E., district engr., Westinghouse Elec. & Mfg. Co., Chicago, Ill.
Rutter, A. R., mgr. of engg., Westinghouse Elec. & Mfg. Co., Newark, N. J.
Stumpf, M. W., asst. elec. engr., New Orleans Public Service, Inc., New Orleans, La.
Warrington, A. R., in charge of application, relay section, General Electric Co., Philadelphia, Pa.
Wollaston, F. O., supt., B. C. Electric Railway Co., Vancouver, B. C., Canada.

17 to grade of Member

Applications for Election

Applications have been received at headquarters from the following candidates for election to membership in the Institute. Names of applicants in the United States and Canada are arranged by geographical District. Any member objecting to the election of any of these candidates should so inform the national secretary before November 31, 1943, or January 31, 1944, if the applicant resides outside of the United States or Canada.

To Grade of Member

Allen, R. C. (Re-election), Gibbs & Cox, Inc., New York, N. Y.
Andrews, R. A., Ward Leonard Elec. Co., Mount Vernon, N. Y.
Bascum, O. A. (Re-election), West. E. & M. Co., Lima, Ohio.
Beaver, G. L. (Re-election), Gen. Elec. Co., San Francisco, Calif.
Bowers, R. H., Mutual Boiler Ins. Co., New Orleans, La.
Braswell, R. W., Louisiana Pr. & Lt. Co., New Orleans, La.
Bratiotis, C. D., U. S. Navy Yard, Portsmouth, N. H.
Cann, W. G. H., Canada Cement Co., Ltd., Montreal, Que., Can.
Choyce, N. B., Loft Candy Corp., Long Island City, N. Y.
Coyne, R. D., Jackson & Moreland, Boston, Mass.
Croft, P. J., Power Corp. of Canada, Montreal, Que., Can.
Daughtrey, L., Jr., Rowan Controller Co., New York, N. Y.
Davison, W. E., Shawinigan Water & Power Co., Montreal, Que., Can.
Emley, P. W., Cutler-Hammer, Inc., Milwaukee, Wis.
Fulton, R. B., Allis-Chalmers Co., Pittsburgh, Pa.
Gregory, P. S. (Re-election), Shawinigan Water & Pr. Co., Montreal, Que., Can.
Haskens, A. J. (Re-election), U. S. Navy, San Pedro, Calif.
Herrington, G. T., Arizona Elec. Power Corp., Flagstaff, Ariz.
Holt, W. A., Baker & Co., Inc., Newark, N. J.
Howard, A. W., Montreal Engg. Co., Montreal, Que., Can.
Johns, W. T., Jr., Rumsey Elec. Co., Richmond, Va.
Jones, R. E., Bail-Horton Co., Jacksonville, Fla.
Littell, C. E., Jr., Lizar-Avia., Inc., Piqua, Ohio.
Moale, E. S. (Re-election), Lieut. Comdr., U. S. Navy Houston, Texas.
Mortara, M., Cons. Gas & El. L. & P. Co., Baltimore, Md.
Ram Prasad, B. K., Jog Hydro Electric Power Scheme, Bangalore, India.
Reid, R. F., Penn. Shipyards, Inc., Beaumont, Tex.
Shelhorse, A. W. (Re-election), Georgia Power Co., Atlanta, Ga.
Shipley, P. F., Bell. Tel. Labs., Inc., New York, N. Y.
Simmons, W. R., Montreal Tramway Co., Montreal, Que., Can.
Tewes, K. H., Sorel Industries, Ltd., Sorel, Que., Can.
Thurling, M. C., Canadian Gen. Elec. Co., Ltd., Montreal, Que., Can.
Weaver, A. B., Rural Electrification Adm., St. Louis, Mo.
Williams, J. A., Pacific Bridge Co., Alameda, Calif.
Zawacki, E. F., Lewis Engg. Co., Naugatuck, Conn.

35 to grade of Member

To Grade of Associate

United States and Canada

1. North Eastern

Bos, J., Eastman Kodak Co., Rochester, N. Y.
Bronaugh, A. T., Jr., U. S. Army, Cambridge, Mass.
Doersam, P. D., Harvard University, Cambridge, Mass.
Dunn, C. H., Univ. of New Hampshire, Durham, N. H.
Hazelwood, C. F., Jr., Gen. Elec. Co., Schenectady, N. Y.
Miller, J. J., General Motors Corp., Rochester, N. Y.
Reid, W., Landers, Frary & Clark, Newington, Conn.
Schwarting, W. H., Western Union Tel. Co., Buffalo, N. Y.
Ware, P. H., Simplex Wire & Cable Co., Cambridge, Mass.
Wilson, W. R., Gen. Elec. Co., Pittsfield, Mass.

2. Middle Eastern

Abbott, H. L., Lieut., U. S. Army, Philadelphia, Pa.
Biedenbender, R., Crosley Radio Corp., Cincinnati, Ohio.
Bond, C. R., Ohio Edison Co., Akron, Ohio.
Bukstein, M., Sig. Corps Insp. Agency, Dayton, Ohio
Burgin, E. R., I-T-E Circuit Breaker Co., Philadelphia, Pa.
Cummins, H. R., Westinghouse E. & M. Co., Mansfield, Ohio.
Fletcher, K. V., Gen. Elec. Co., Philadelphia, Pa.
Geiz, J. F., Roller Smith Co., Bethlehem, Pa.
Hoffecker, J. L., Westinghouse E. & M. Co., Akron, Ohio.
Lomis, I., United Engr. & Constr., Inc., Philadelphia, Pa.
Mason, H. M., U. S. Maritime Comm., Washington, D. C.
Moore, F. B., Cons. Molded Prod. Corp., Scranton, Pa.
Morgan, R. H., West. E. & M. Co., Sharon, Pa.
Parker, L. L., Glenn L. Martin Co., Baltimore, Md.
Randolph, H. T., Washington Sub. San. Comm., Hyattsville, Md.
Rix, R. W., Cleveland Elec. Ill. Co., Cleveland, Ohio.
Stewart, E. W., Phila. Elec. Co., Philadelphia, Pa.
Sutton, D. E., I-T-E Circuit Breaker Co., Philadelphia, Pa.
Watkins, J. E., Phila. Sig. Corps Proc. Dist., Philadelphia, Pa.

3. New York City

Barlow, W. A., General Winding Co., New York, N. Y.
Christiansen, E. G., Ward Leonard Elec. Co., Mount Vernon, N. Y.
Hovemeyer, W. E., Newark Sig. Corps Insp. Zone, Newark, N. J.
Kahn, E. L., S. W. Farber, Inc., Brooklyn, N. Y.
Kettell, J. E., H. A. Fraser, Inc., New York, N. Y.
Kouridis, G. T., Newark Sig. Corps Insp. Zone, Newark, N. J.
Kunin, W., Ward Leonard Elec. Co., New York, N. Y.
Lathrop, C. M., Standard Oil Dev. Co., Elizabeth, N. J.
Lessner, H. W. (Re-election), Westinghouse E. & M. Co., Newark, N. J.
Littlejohn, H. F., Jr., Ward Leonard Elec. Co., New York, N. Y.
Mainberger, W. A., College of City of N. Y., New York, N. Y.
McGowan, F. J., Anaconda Wire & Cable Co., Hastings-on-Hudson, N. Y.
McHale, F. J., M. W. Kellogg Co., New York, N. Y.
Michaels, S. J., Anaconda Copper Mining Co., New York, N. Y.
Mozzi, F. J., Newark Sig. Corps Insp. Zone, Newark, N. J.
Nidzyn, J. J., Fairchild Aviation Corp., New York, N. Y.
Peterson, O. G., Sperry Gyroscope Co., Brooklyn, N. Y.
Pyna, T. F., Capt., U. S. Army, Red Bank, N. J.
Ryan, T. R. (Re-election), Amer. Steel & Wire Co. of N. J., New York, N. Y.
Sundell, C. W., E. B. Badger & Sons Co., New York, N. Y.
Torch, H. T., Lieut., U.S.N.R., Tompkinsville, N. Y.
Townend, W. H. S., Newark Sig. Corps Insp. Zone, Newark, N. J.
Zabardis, N. G., Lieut., U.S.M.S., Brooklyn, N. Y.

4. Southern

Hemker, H. F., Gen. Elec. Co., Memphis, Tenn.
Kastner, R. M., Ensign, U. S. Navy, Portsmouth, Va.
Segall, B. (Re-election), New Orleans Pub. Serv., Inc., New Orleans, La.
York, J. M., Allis-Chalmers Mfg. Co., Charlotte, N. C.

5. Great Lakes

Casteel, D. O., Bendix Prod. Div., South Bend, Ind.
Cohn, G. L., Lieut., U. S. Army, Lake Forest, Ill.
Donnelly, A. V., Iowa State Univ., Iowa City, Iowa.
Hill, W. D., Commonwealth Edison Co., Pekin, Ill.
Kramer, F. C., Naval Training School, Ames, Iowa.
Kuhn, H., Kurz & Root Co., Appleton, Wis.
McKnight, B. E., Gen. Elec. Co., Fort Wayne, Ind.
Oden, C. M., Commonwealth Edison Co., Chicago, Ill.
Pharmer, W. L., Gen. Electric Co., Fort Wayne, Ind.
Poer, N. V., Gen. Motors Corp., Anderson, Ind.
Rouse, W. H., Cutler Hammer, Inc., Milwaukee, Wis.
Sawyer, R. A., Gen. Elec. Co., Fort Wayne, Ind.
Schlicher, D. W., Iowa State College, Ames, Iowa.
Schulte, R. F., Gen. Elec. Co., Fort Wayne, Ind.
Stephens, T. C., Iowa State Univ., Iowa City, Iowa.
Taskin, H. A. K., Marquette Univ., Milwaukee, Wis.
Thibodeau, A. J., Ford Motor Co., Dearborn, Mich.

6. North Central

Binney, W. L., City of Lincoln Water & Lt. Dept., Lincoln, Nebr.
Hampton, P. E., Loup River Pub. Pr. Dist., Columbus, Nebr.
Kester, S. J., Gen. Elec. Co., Denver, Colo.
Porter, W. A. (Re-election), Pub. Serv. Co. of Colo., Denver, Colo.
Shute, C. D., Pub. Serv. Co. of Colo., Denver, Colo.

7. South West

Adams, S. L., Gulf States Utilities Co., Beaumont, Tex.
Boyd, R. L., Westinghouse E. & M. Co., St. Louis, Mo.
Cady, W. M., Penn. Shipyards, Inc., Beaumont, Tex.
Cloninger, F. M., Pub. Serv. Co. of Okla., Tulsa, Okla.
Collins, D. O., Union Elec. Co. of Mo., Festus, Mo.
Dill, J., Jr., Kansas Gas & Elec. Co., Wichita, Kans.
Dry, J. E., Superior Elec. Co., Dallas, Tex.
Gibson, J. V., U. S. Engineers, Denison, Tex.
Glidden, D. L., Graybar Elec. Co., Inc., Houston, Tex.
Gosnell, R. F., Southwestern Bell Tel. Co., St. Louis, Mo.
Hopkins, R. O., Gulf States Utilities Co., Beaumont, Texas.
Jansen, C. H., Lummus Co., Houston, Tex.
Jenkins, J. H., Sandford Cons. Co., Oklahoma City, Okla.
Kinzer, E. F., Houston Ltg. & Pr. Co., Houston, Texas.
Kongabel, H. J., West. E. & M. Co., El Paso, Tex.
Lehmberg, M. M., Houston Ltg. & Pr. Co., Houston, Tex.
Parmelly, J. H., Humble Pipe Line Co., Odessa, Texas.
Plumer, W. H., Southwestern Bell Tel. Co., Tulsa, Okla.
Stuemky, E. R., Southwestern Bell Tel. Co., Tulsa, Okla.
Sutter, C. H., Kansas Gas & Elec. Co., Wichita, Kans.
Sutton, H. J., Gulf States Utilities Co., Beaumont, Tex.
Taulman, J. W., Jr., Lock Insulator Corp., Dallas, Tex.
Terhune, R. S., Nelson Mfg. Co., Tulsa, Okla.
White, J. H., Rural Electrification Adm., St. Louis, Mo.

8. Pacific

Bjerrum, L. N., Douglas Aircraft Corp., El Segundo, Calif.
Coklis, O. E., Cons. Vultee Aircraft Corp., San Diego, Calif.
Daniell, H. E., Moore Dry Dock Co., Oakland, Calif.
Humphrey, E. L., Fischbach & Moore, Inc., Richmond, Calif.
Meisenheimer, L. F., Lieut. (j.g.), U. S. Navy, San Francisco, Calif.
Ossin, J. S., U. S. Navy, San Francisco, Calif.
Roosenberg, P., San Diego Gas & Elec. Co., San Diego, Calif.
Snyder, L. G., Lieut., U.S.N.R., Burbank, Calif.
Starr, A. B. (Re-election), U. S. Govt. Pub. Wks. Dept., San Diego, Calif.
VanWagenen, H. W., Parker Elec. Supply, Parker, Ariz.

9. North West

Crosby, R. E., Washington Water Pr. Co., Spokane, Wash.
DeCourcey, D. G., Boeing Aircraft Co., Seattle, Wash.
Levin, E., Boeing Aircraft Co., Seattle, Wash.
Sander, W. C., Wash. Water Power Co., Spokane, Wash.
Schlief, F. R., U. S. Bur. of Reclamation, Coulee Dam, Wash.
Seibel, R. C., Montana State College, Bozeman, Mont.
Westlake, P. R., 1st Lieut., U. S. Army, Seaside, Oreg.
Wollert, A., Capt., U. S. Army, Fort Lewis, Wash.

10. Canada

Cuff, J. V., Amalgamated Electric Corp., Ltd. Toronto, Ont., Can.
Phelan, A. J., Northern Elec. Co., Montreal, Que., Can.
Ross, V. B., Canadian Gen. Elec. Co., Toronto, Ont., Can.

Elsewhere

Bogen, S., Scowe Elec. Pty., Ltd., Sydney, Aus.

Total to grade of Associate
United States and Canada, 123
Elsewhere, 1

OF CURRENT INTEREST

New Frontiers in Rubber Revealed in Recent Address

One of the greatest problems facing the rubber industry today is that of improving the quality of synthetic rubber, Edwin J. Thomas, president of the Goodyear Tire and Rubber Company, Akron, Ohio, stated in a recent address before the Engineering Society of Detroit.

After months of confusion and countless experiments, he reported, a new material has been evolved which will be the basis of rubber manufacturing in the United States at least for the duration of the war. Although the postwar position of synthetic rubber is still a matter for much conjecture, various factors indicate that it will take its place beside crude rubber according to the future value of each.

In order to present the status, and the future direction of the rubber program now in operation, Mr. Thomas briefly reviewed the beginnings of the rubber crisis. The essential substance of his address, "New Frontiers in Rubber," follows.

The United States always has been the largest consumer of rubber among the nations of the world. In the years before Pearl Harbor, the average annual consumption of crude rubber was somewhat more than a half-million tons, most of which came from halfway around the world.

Because of the great distances involved, it had been necessary and customary to keep approximately six months' supply of crude rubber on hand in this country. But when the war broke out in Europe in 1939, the country's inventories were at an extremely low level—125,000 tons, or only two months supply. Our reserve was subnormal because the price of crude rubber, fixed through British–Dutch agreements, was too high to make normal forward buying advisable.

Bitter experience with rubber shortages in World War I led the rubber industry to begin urging the government to build up more substantial crude-rubber inventories against a possible emergency. For its part, the industry began to build up its own stocks insofar as it was financially able, but it lacked the funds for a heavy gamble in such a highly volatile market. Furthermore, to provide national insurance in time of war, huge rubber reserves were needed for which only the government could make the necessary arrangements. Accordingly they were made, and the government's reserve stock of rubber began to grow.

Besides advocating government-created stockpiles of crude rubber, private industry urged the government to establish a number of small synthetic plants—test cases which would lead to knowledge of and experience in the production and handling of synthetic rubber, and which would furnish the pattern for plant design and production formulas. Pending government action, some of the companies set up such small plants at their own expense.

When the Japanese attack was launched against us at Pearl Harbor, our crude-rubber stockpile had been increased from 125,000 to 533,000 tons, and four months later it had been built up to 634,000 tons. This was more than a normal year's supply but less than was consumed during the peak year 1941, when 775,000 tons of rubber were processed to meet the high production of the automotive industry, the forward buying of the public, and the developing military needs.

Concurrent with this reserve came strenuous conservation in the use of existing rubber products in the form of low speed limits, mileage and tire rationing, and similar precautions. Efforts were made to accumulate large supplies of scrap rubber, and to develop the sources of jungle rubber—guayule, cryptostegia, and others. Every ounce of rubber of any description assumed the stature of a national asset.

At this time, in broad outline, the rubber problem could be analyzed in terms of simple arithmetic:

1. There was so much crude rubber on hand, plus unused mileage in the tires on the wheels.

2. A minimum of so much rubber would be required for the prosecution of the war and the maintenance of the home front.

3. There remained only so much time in which to provide a substitute supply before existing stocks were exhausted.

Those were its basic elements. They were not exact to the last pound or the last day, but their approximations afforded an ample base for emergency planning. In the face of these fixed facts, however, there ensued a period of utmost uncertainty and confusion. All manner of unsound proposals were brought forward, and to the bewilderment of public thinking, most of them made the front pages of the daily newspapers.

Fortunately for America, the scientific researchers of the rubber industry possessed a sound working knowledge of the synthetic field, both at home and abroad. It was known that the Germans had been working along this line since shortly after the first World War. Representatives sent to discover their progress, although for the most part given a polite run-around, satisfied themselves that the United States had kept abreast of all developments over there. At home, several industries were working indefatigably on independent research and comparing notes. Even the universities began directing their graduate research toward this problem.

Then the Japs struck at Pearl Harbor. A few months later they had conquered Malaya and the East Indies—the source of 90 per cent of our crude-rubber supplies. It was then, of all times, that the era of confusion developed.

On the side of definite action, the Rubber Reserve Corporation had been created to handle the stockpiling and to initiate a synthetic-rubber plant-building program. But on the side of unfinished business there was a massing of detail. Designs for butadiene and styrene plants needed completion. The best standard process for manufacturing synthetic rubber had to be decided upon. The size of the program was still to be determined. Most of the processing and converting problems of the manufacturer remained to be perfected. Labor and materials became short, and military and civilian authorities squabbled over the right to obtain what critical materials were available.

It was not until September 1942—nine months after Pearl Harbor—that the Baruch report, made by the committee consisting of Bernard Baruch, chairman; Doctor Karl T. Compton, president of Massachusetts Institute of Technology; and Doctor James B. Conant, president of Harvard University, brought an end to this confusion and fixed our national course. As called for by the report, a rubber director, William M. Jeffers, was appointed. He accepted the objectives fixed by the report as a definitive course of procedure, and the program was undertaken at once.

In detail, the program called for establishing 14 polymerization plants for the manufacture of buna *S* rubber, with 23 plants for butadiene and seven plants for styrene. Three plants for butyl and one for neoprene were included. The total capacity was to be 850,000 long tons, which called for a government outlay of over half a billion dollars. The plants were to be owned by the government and operated by the various oil, chemical, and rubber companies, and the whole program had to be completed ahead of the time when our existing stocks of crude rubber would be depleted.

Under the spur of possible military defeat, technical problems of plant design and operations were worked out. Even while the technicians were agreeing upon such matters, contractors and producers of building materials and manufacturing machinery were straining every effort to beat a fateful deadline.

Today those great butadiene, styrene, and polymerization plants are fast coming into full production. Meanwhile, the rubber manufacturers had cut their usage of crude rubber from 775,000 tons in 1941 to 377,000 tons in 1942, and the 1943 con-

sumption has been reduced further to 300,000 tons. At the same time, 175,000 tons of synthetic production will be available this year.

At the beginning of 1944 at least 125,000 tons of crude rubber will still remain in our national stockpile, with synthetic plants producing at a rate of 800,000 tons per year. From 35,000 to 50,000 tons of crude rubber will be imported from Latin America, and an additional 100,000 tons will be added to the United Nations' pool from Ceylon and Africa.

These figures bring the rubber program up to date factually. But how to interpret them in regard to future developments?

As the situation stands now, for general purposes, synthetic rubber is not equal to crude rubber in performance or adaptability. The greatest drawbacks are its lower elasticity, and its lower elongation which tend to shorten progressively under the influence of heat and aging. One of its good points is its abrasion resistance.

Another important drawback is the effect on processing capacities when synthetic rubber is used. There is a 20 to 25 per cent reduction in processing capacity, particularly in connection with milling and mixing operations. It simply takes longer to get the rubber in shape to use for the processes that follow. More machinery with higher priority ratings is needed without delay to circumvent this loss.

Then, there is the quality of the product as compared with that made from crude rubber. At present, no tire made from synthetic rubber will equal the best crude-rubber tire in performance. In passenger-car tires made with 100 per cent synthetic rubber, the American motorist will find adequate satisfaction if he observes the present speed limits. There will be some problems with cutting and chipping of the treads, and more bruising and separation at higher speeds, but they will wear reasonably well.

However, truck tires made of 100 per cent, or a high percentage of synthetic rubber, present many more difficulties, especially in the larger sizes, where speed and load make the generation of heat a serious problem. This handicap, present in prewar tires made from crude rubber, is heightened by the use of synthetic rubber. A great deal of tread cracking, tread cutting, and separation is experienced, and many blowouts occur. Some new tread designs appear helpful. Truck tires built of rayon cording stand up much better than those from cotton cord, and treads built less thick wear best under the severe heat conditions. Technical men of the United States Army, the government, and the rubber industry are concentrating on this problem. However, truck tires will be made from one-half crude rubber and one-half synthetic rubber until these difficulties can be overcome.

At the present time, the rubber industry is running at peak capacity. In addition to a huge military load, an essential civilian load must be met now. For 1944, the military demand has increased over that in 1943, and much of this comes in large-size truck and airplane tires that require the greatest amount of labor, space, and milling capacity. Also, civilian truck needs will be the greatest in history, and tractor tires for food production will further tax production facilities.

Ordinarily, civilians need 30,000,000 to 35,000,000 new tires each year to keep their cars running. Since tire rationing, the public has been provided with only about 17,000,000 tires—5,000,000 synthetic passenger tires, 7,000,000 from pre-Pearl Harbor stocks, and 1,000,000 fully reclaimed tires—plus recaps. One of the greatest national assets was the quality and available mileage in the tires on the cars of Americans when the supply of crude rubber was cut off.

With synthetic rubber available, the industry is faced with supplying a minimum of 30,000,000 new tires to keep the essential cars operating in 1944. Whether it can do this as well as carry the military demands will depend upon getting more production from present machinery, quickly securing additional capacity, its ability to secure sufficient cord and rayon fabric, and upon relief from the man power shortage.

The best postwar future for the rubber industry will be in the products it furnished before the war. The demand for renewal tires will be enormous. Tires for original equipment will be needed in greater quantities than ever before. Huge vacuums, created by wartime shortages, must be filled in all rubber products.

In the postwar world there will be new and better machines in rubber processing. A huge field in insulation lies ahead. One product in this line now in operation seems to do an outstanding job in fulfilling military needs. The field of vibration damping is opening up. The use of Pliofilm, a rubber resin in sheet form, for wrapping packages, fruits, machinery, airplane engines, and so forth, is almost unlimited, as well as rubber- and resin-coated papers. The use of rubber for flooring and walls is almost untouched. New yarns and fibers now under development will make better products. Various plastics, with and without rubber, can be used with advantage to the rubber companies. Man-made rubber offers an opportunity of adapting this basic material to fit a variety of requirements never possible heretofore.

United States Replaces Germany in Developing Uruguayan Power

With United States engineering and financing replacing German on a Uruguayan dam project brought to a standstill by that country's severing relations with the Axis nations in 1942, the project is expected to begin delivering power in 1945.

Located on the Black River which crosses the entire country from northeast to southwest, the new dam will add 121,600 kw to Uruguay's present power capacity of 110,000 kw. The contract for the first of the four 30,400-kw waterwheel generators has been awarded to the International General Electric Company. The unit will stand 25 feet high with an over-all diameter of 39 feet. Funds for completing the project were obtained from a United States Export–Import Bank loan of $12,000,000 to the Uruguayan government. Prior to the Black River project the country's only large power stations were two steam plants in Montevideo. The rest of the country, which supports two thirds of the population of $2,500,000 persons, was supplied chiefly by isolated plants operated by imported oil. When the war cut off imports, Uruguay was confronted with power shortages which threatened to become as serious as those in Argentina, where, because of coal shortages, one ton of corn must be added to three of coal in steam-power stations.

The increased power supplied by the dam is expected to change present conditions, whereby the majority of manufacturing plants are concentrated at Montevideo, and cause industrial expansion in the hinterland. Rural electrification, flood control, irrigation, river transportation facilitating trade between the farms and the industrial markets, and increased mining activity are among the other benefits the dam will provide throughout the 26,000 square miles drained by the 530-mile Black River.

The dam itself, 130 feet high and 3,850 long, will create a normal storage of about 9,000,000 acre-feet, while additional flood storages of 3,000,000 acre-feet are contemplated. The lake built up by the dam will extend upstream for 87 miles with a maximum width of 18 miles.

WPB Studies War Uses for Stained Mica

Finding a war use for the surplus of lower-grade mica now accumulating in government stockpiles is occupying a research program instituted by the War Production Board. WPB's success in increasing the supply of the better-quality mica is responsible for building up stocks of mica rejected under present standards for uses other than electrical insulation, spark plugs, and some radio tubes. If the results of this new program are satisfactory there will be a supply of the stained qualities of mica sufficient to compensate for the shortage of the clearer qualities.

Since the manufacture of capacitors is the greatest single use for mica, the National Research Council has set up a research project at Bell Telephone Laboratories, Inc., to reconsider the types of mica that might be suitable for their manufacture.

In the course of its mica-testing program, instruments that will measure the electrical qualites of mica have been developed by the laboratories. By means of these instruments various inferior qualities of mica were found to be free from conducting veins and spots, and as low in power loss as mica free from stain. A limited number of capacitors made from the stained mica seemed to indicate that in most respects the capacitors are as satisfactory as those fabricated from the better-quality mica.

On the basis of this preliminary work, the WPB took a wider sampling of the mica heretofore termed inferior. Additional sets of testing instruments were built, and nine different types of mica not ordinarily used for capacitors, six of domestic and three of foreign origin, were tested. Tested at that time was 1½ tons of mica which has now been distributed among various manufacturers for use in assembling specified capacitors. These capacitors must then measure up to the usual performance specifications of the armed forces.

Anticipating that the capacitors will pass military inspection and that the stained mica then will be admitted into general usage, the American Society for Testing Materials is preparing necessary specifications covering natural block mica for use in capacitors, and it is expected that tentative standards soon will be adopted. To meet the specifications under consideration, the mica must test satisfactorily on the Bell Laboratories' instruments for power loss and absence of conducting veins and spots and must meet such physical standards as flatness, ease of cleavage, hardness, and freedom from cracks and pinholes. Use of the instruments does not obviate the need for visual inspection which alone can discover such defects as excessive waviness, softness, and the presence of minute particles of rock.

Although all the mica tested to date is included in the present buying program of the Colonial Mica Corporation (the government agency), and no change in procurement policy will be made until the testing has been completed, preparations for a new buying program are being made. Samples of mica from all principal domestic mines including those now supplying the Colonial Corporation and those now considered to be nonstrategic are being tested. The facilities of the Corporation's offices at Asheville, N. C., Newport, N. H., and Custer, S. Dak., are available to neighboring mines. Operators of mines considered nonstrategic are urged to contact the nearest office to arrange for samples to be tested. A statement of the results then will be given the mine operator.

Technical Advisory Service Available to Small Plants

A technical advisory service, set up by regions throughout the United States to serve the interests of small plants, has been established recently by the Smaller War Plants Corporation, according to Brigadier General Robert W. Johnson, chairman. The service will put at the disposal of the small manufacturer who requires technical research in the solution of a production problem information drawn from government agencies, trade associations, technical and scientific organizations, technical-magazine editors, and the research laboratories of educational institutions and private industry.

The service derives from an idea that has been applied successfully in private business since 1937 by Bert. H. White, vice-president of the Liberty Bank of Buffalo, N. Y., who is now on leave as a major in the United States Army Air Forces in order to establish the technical advisory service. A six-week indoctrination course, given by Major White at the University of Buffalo, trained representatives from each of the 14 SWPC regional offices in the administration of the technical advisory service.

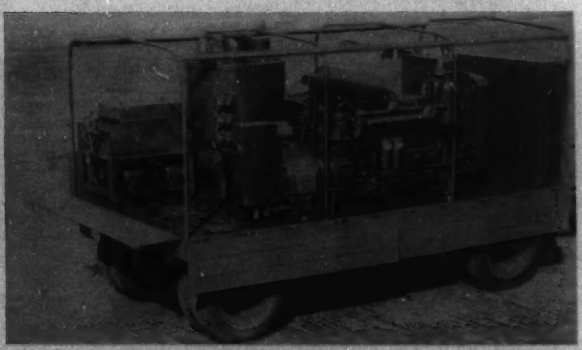
The service itself does not engage in industrial research or testing, and for the most part is available without charge to all small manufacturers. In a few cases, where the nature of the information sought is such that it can be obtained only from commercial testing laboratories or professional service organizations, the technical advisory consultant will recommend several recognized leaders in that field.

Labor Department Sponsors Industrial Safety Campaign

Under the sponsorship of the Division of Labor Standards of the United States Department of Labor, 550 safety engineers will donate 20 per cent of their time to aiding a national campaign to conserve man power for war production. Any plant management may secure the service of one of these engineers simply by requesting it. After a consultation the safety engineer will analyze the safety training needs of the plant. He will supply information about existing courses in safety training and help enroll qualified workers.

As an additional part of the safety campaign, standard basic courses of 96 hours on principles and techniques of industrial safety have been organized. Located in industrial centers for the convenience of workers these evening classes are offered for two groups: key supervisory employees and members of joint safety committees—both union and management representatives. The Division of Labor Standards prepares training aids: outlines, guides, textual material, references, supplementary pamphlets, and bulletins. The United States Office of Education through its Engineering, Science, and Management War Training Program, pays the costs of the courses and local engineering colleges sponsor them.

Trailer Solves Lubrication Problems



This mobile lubricating-oil reclaimer for use behind the fighting line has been designed, built, and delivered to the United States Marine Corps by the Youngstown Miller Company, Sandusky, Ohio. On the trailer unit is a standard Y-M reclaimer, a Diesel-electric generating set, a clean-oil storage tank, a fuel-oil tank, and waterproof storage bins for refinery earths, filter papers, and spares. In operation, a charging pump conveys the dirty oil from drums on the ground to the heating tank, where, in intimate contact with refinery earth, it is brought to a temperature sufficient to dissipate the volatiles. Then the oil is dropped into a transfer tank and forced through a two-stage filter to clean-oil receiving drums by compressed air

OCD Establishes National Security Award. Establishment of a National Security Award recognizing outstanding plant security programs and formation of a national board of review to pass on the protection and security records of plants otherwise eligible for the award, were made recently by the Office of Civilian Defense. Not limited to munition manufacturers, but including manufacturers of essential civilian goods, public utility organizations and other essential establishments, the award will be granted by the OCD for achievement in protection of employees,

physical property, and production processes against air raids, fire, sabotage, accident, and other dangers. The board of review, composed of delegated representatives of seven major labor, management, and safety organizations, is: Percy Bugbee, National Fire Protection Association; P. L. Hardesty, Chamber of Commerce of the United States; R. E. Wilson, National Bureau for Industrial Protection; G. J. Richardson, International Association of Fire Fighters; E. S. Webb, National Safety Council; C. G. Goff, Brotherhood of Locomotive Firemen and Enginemen; and T. M. Brennan, National Association of Manufacturers.

Wider Subcontracting of Orders for Test Equipment Planned

To meet increasing requirements of the armed services for electronic test equipment, a plan for wider subcontracting of orders for critical test equipment, test instruments, and component parts has been initiated by the radio and radar division of the War Production Board. Suggested items for subcontracting include:

1. Those models having a relatively small volume of sales. This releases productive capacity for the large volume models requiring the prime contractor's special skill.

2. A part, or all, of the order for a model having a large backlog.

3. Component parts.

Regional offices of the WPB have been requested to furnish detailed reports on manufacturers and facilities available for prime contracts or subcontracts for this apparatus. At the same time, each manufacturer of electronics test equipment has been asked to indicate which firms would be most capable of adapting themselves to produce, under subcontract, items for his schedule.

Premature Grenade Explosions Prevented. An automatic X-ray machine, which accurately checks the proper amount of powder needed to prevent the grenade's exploding as soon as a soldier releases his grip on the handle has been devised by the General Electric Company at the request of the army. This machine, the first of its kind in the country, will check 4,000 fuses an hour. The metal grenade fuses, slightly larger but similar in appearance to a clinical thermometer, are passed through the machine on a movable belt. The perpendicular beam of a 100,000-volt X ray penetrates each fuse and casts its glow on a fluorescent screen above which is a phototube of "electric eye." Should a fuse with a light powder charge pass over the X-ray beam, the phototube detects the change in the fluorescent glow, rings a bell, flashes a red light, places a dab of red paint on the fuse, and records the "dud" graphically on a meter chart. This four-way check makes it impossible for a defective fuse to pass undetected.

OTHER SOCIETIES •

ASCE Adopts Program for Postwar Construction

Despite the fact that the United States now is engaged in total war, a program of both private and public construction projects of immediate and unquestioned usefulness that can be planned now and undertaken after the war is essential if man power now engaged in the war effort is to be absorbed quickly into peacetime pursuits. Such is the basis of a program recently adopted by the board of direction of the American Society of Civil Engineers, for stimulating plans for postwar construction. The program was outlined by the society's committee on postwar construction, under the chairmanship of G. Donald Kennedy. To execute the work of the committee and to enable the society to assist local bodies in the development of such a program, the board approved the appropriation of $15,000 to permit employment of a full-time member of the society's staff.

Basic to the society's program is the fact that the great program of war construction has almost been accomplished, and that soon there will be available a large number of experienced engineers and architects, many of them above military age or incapable of combat duty, whose services could be employed effectively in the preparation of detailed plans and specifications for useful postwar construction projects. Also basic to the society's program are the recommendations that these projects be developed under the existing contract system, and that promptness be exercised in letting contracts immediately after the cessation of hostilities.

Under the leadership of the Committee of Economic Development, industry already is evolving tangible plans for conversion to peacetime production designed to satisfy the accumulated postwar demand for durable and consumer goods. An essential part of this industrial activity will be the alteration or construction of plant facilities. Some plants with greatly expanded facilities will require little adaption; plants of pure war utility may be dismantled; and older facilities that have become obsolete will require modernization or replacement.

An acute demand for new private housing is expected to manifest itself as soon as wartime limitations are lifted. An early start on this housing can be made through stimulation of the advance purchase of sites for individual homes or housing projects, and through the advance completion of plans and specifications.

The successful administration of a public-works program, the ASCE statement says, depends upon the way in which it balances with the other forces of national economy, its readiness to be set in motion in time of emergency, and the nature of the projects it fosters. From past reports it is known that industry and private housing account for approximately two thirds of all construction activities, and that only the remaining third can be devoted to public works if equilibrium is to be maintained. Then, too, it is not enough to catalogue or list the projects under consideration, with approximate estimates of their costs and indications of how they may be financed. The real need is that means be provided for complete preparation *now* of actual plans and specifications and other preliminary work relating to rights of way, means of financing, and the acquisition of property rights. Common sense dictates the selection of projects that will create the proper balance between immediate postwar needs and long-range construction planning.

It is also essential that the public works program, while adding to the wealth of the country, does not involve too severe a tax burden on the people. Most states have laws that permit financing certain types of public improvements on a revenue-bond basis. Such bonds are not a general public tax obligation but an obligation retirable out of the earnings of the projects themselves, derived from payments made by the actual users. Projects coming into this classification include water supply and distribution systems; water purification plants, sewerage systems, and sewerage-disposal plants; public swimming pools; hospitals; large housing projects; public markets; off-street parking facilities; street improvements giving access to private property; express and limited highways, highway tunnels, and toll bridges; and irrigation and drainage projects.

Outstanding bond issues for public improvements which are not of this self-liquidating nature are being paid off during the war period to such an extent that many local political units can incur additional bond indebtedness within legal limitations. These projects include schools; parks and recreational facilities; libraries; buildings for housing local government agencies such as city halls, courthouses, and jails; flood-control projects of local significance; public health centers; state penitentiaries; state hospitals for the insane and feeble-minded; state homes for orphans or the aged; buildings for state universities or other public institutions of higher learning; and public highway and urban street improvements.

Some state and local laws or other similar obstacles may prevent the immediate financing of planning for local public works. Where this is the case it may become necessary for Congress to authorize a revolving fund, and a system of making loans under proper safeguards, as a means of getting such work under way.

As regards federal public works, agencies engaged in various forms of construction for the federal government are already surveying projects which could be undertaken profitably. The ASCE program recommends that appropriations be made now so that these departments may proceed promptly in preparing detailed plans and specifications. Before undertaking these projects, it should be ascertained that they have practical utility and are sound economically, and that they do not compete with facilities provided through private enterprise.

Future Meetings of Other Societies

American Institute of Chemical Engineers. 36th annual meeting, November 15–16, 1943, Pittsburgh, Pa.

American Institute of Mining and Metallurgical Engineers. Annual meeting, February 20–24, 1944, New York, N. Y.

American Society of Heating and Ventilating Engineers. 50th annual meeting, January 31–February 2, 1944, New York, N. Y.

American Society of Mechanical Engineers. Annual meeting, November 29–December 3, 1943, New York, N. Y. Spring meeting, April 3–5, 1944, Birmingham, Ala. Semiannual meeting, June 19–20, 1944, Pittsburgh, Pa.

Engineering Institute of Canada. Annual meeting, February 1–11, 1944, Quebec, Que.

Exposition of Chemical Industries. December 6, 1943, New York, N. Y.

National Fire Protection Association. May 8–11, 1944, Philadelphia, Pa.

Society of Naval Architects and Marine Engineers. 50th anniversary and annual meeting, November 10–13, 1943, New York, N. Y.

Physicists Acquire New Headquarters. As the first step in the program for the development for physics outlined by the war-policy committee of the American Institute of Physics, a new national headquarters' building at 57 East 55th Street, New York, N. Y., has been purchased by that institute. According to present plans, the institute expects to occupy the new headquarters by January 1, 1944. Financing of the project is being accomplished through subscriptions from physicists and others interested in physics. A goal of $75,000 has been set in order to provide the necessary funds for the purchase of the property. Present headquarters of the institute is at 175 Fifth Avenue, New York, N. Y.

HONORS

AIME Awards Three Medals

The awarding of the Charles F. Rand Memorial Medal to Cornelius F. Kelly, chairman of the board, Anaconda Copper Mining Company, Butte, Mont.; the Anthony F. Lucas Gold Medal to Charles V. Millikan, chief petroleum engineer of the Amerada Petroleum Corporation, Tulsa, Okla.; and the William Lawrence Saunders Gold Medal to George B. Harrington, president of the Chicago, Wilmington and Franklin Coal Company, Chicago, Ill., was announced recently by the American Institute of Mining and Metallurgical Engineers.

Mr. Kelley, who received the award for "distinguished achievement in mining administration," has been associated with the copper industry since 1892. After studying law at the University of Michigan, he entered the legal department of the Anaconda Copper company in 1901 and in 1908 became general counsel. In 1911 he was made vice-president and in 1918 became president and director.

The 14th recipient of the Saunders Medal for "distinguished achievement in mining," Mr. Harrington, has been with the Chicago, Wilmington and Franklin company since 1914. He was graduated from Princeton University in 1902 and from the Massachusetts Institute of Technology in 1904.

Mr. Millikan, the sixth recipient of the Lucas Medal for "his outstanding contributions to engineering in the development and production of petroleum," attended the Oklahoma Agricultural and Mechanical College and the University of Pittsburgh. After obtaining experience in the mid-continent and Appalachian oil fields, he joined the Amerada corporation in 1922.

SPEE Awards Lamme Medal to Thomas Ewing French

Thomas Ewing French, professor and head of the department of engineering drawing, Ohio State University, Columbus, is the 16th recipient of the Lamme Medal of the Society for the Promotion of Engineering Education. Professor French is commended for "his genius in teaching the graphical language of engineering; his facility in producing successful textbooks of engineering drawing . . the breadth of his personal culture . . his perennial interest in students . . his guidance of the athletic problems of his University" in the citation accompanying the award.

Professor French, who was born in Mansfield, Ohio, in 1871, graduated from the course in mechanical engineering at Ohio State University in 1895. In 1922 Monmouth College conferred the honorary degree of doctor of science upon him. He was appointed head of the department of engineering drawing at Ohio State University in 1906. Author of many texts and articles on drawing and lettering, he was the first author to substitute the name engineering drawing for mechanical drawing and is a contributor to the *Encyclopedia Britannica*. He is a past president (1927–28) and council member (1916–19) of the SPEE. Professor French is also a fellow of the American Association for the Advancement of Science and a member of the American Society of Mechanical Engineers, the Newcomen Society, Phi Beta Kappa, Sigma Xi, and Tau Beta Pi.

IES Establishes New Award

An award of a gold medal intended to give "recognition to meritorious achievement which has conspicuously furthered the profession, art, or knowledge of illuminating engineering," has been established by the Illuminating Engineering Society. The new medal will not be awarded annually nor, in fact, at any stated interval. It is to be awarded from time to time as it is merited but not more than once a year. Final decision on the presentation rests with the Society's council which will consider the recommendations of a committee on award.

Candidates for the award, either members or nonmembers of the Society, may be nominated at any time by a member or associate member of the IES. The candidate's name and record of achievement must be submitted to a special committee on award. Achievement in the fields of engineering, design, applied illumination, optics, opthalmology, lighting research, education, or administration and management will be considered.

The committee on award will be composed of nine members—two thirds drawn from among the past presidents of the Society and one third from the membership at large.

Kennedy Medal Awarded by Engineering Institute of Canada. The Sir John Kennedy Medal, which is awarded as occasion warrants for outstanding merit in the engineering profession and outstanding contribution to the science of engineering, has been awarded to C. J. Mackenzie, dean of engineering, University of Saskatchewan, Saskatoon, the Engineering Institute of Canada announced recently. Doctor Mackenzie holds the degrees of bachelor of engineering from Dalhousie University and master of civil engineering from Harvard University. He was awarded honorary doctorates by Dalhousie University and McGill University in 1941. He first joined the faculty of Saskatchewan University in 1912 and has been dean since 1921. Active in civil affairs, he has practiced as consulting engineer in western Canada. Since 1939, when he succeeded A. G. L. McNaughton (HM '42) he has been acting president of the National Research Council at Ottawa, Ont., and is a past president of the Engineering Institute of Canada.

INDUSTRY

Consumption of Electric Power Increased in Brazil

Aggregate sales of electric power in Rio de Janeiro, Sao Paulo, and Santos, Brazil, totaled 1,984,000,000 kilowatt-hours in 1942, according to the annual report of the Brazilian Traction Light and Power Company, Ltd., which, through affiliated companies, controls the electricity supply in those areas. This total represents an increase of 8.4 per cent more power than that consumed in 1941, and was distributed among 622,051 customers—30,116 more than in 1941.

The capacity of generating plants rose from 556,509 kw in 1941 to 591,509 kw in 1942, and the total connected load rose from 1,286,890 kw to 1,392,522 kw. Approximately 30 miles were added to the transmission system, making the total length of lines in operation 2,083 miles.

Distribution lines, mostly overhead, measure 32,066 miles.

Vegetable Fuels Used for Part of Argentina's Electric Power

More than one third of the 390,000,000 kilowatt-hours generated by Cia. Italo-Argentina de Electricidad of Buenos Aires, Argentina, in 1942 was produced by using vegetable fuels, according to the foreign press. During the year, two boilers at the New Port station were altered so that pulverized cereals could be used for fuel, and two others were converted to burn corn. Vegetable fuels were used also in the Pedro Mendoza station. In both instances it was necessary to install special handling, storage, and pulverizing equipment to take care of the new type of fuel.

Exposition of Chemical Industries to Be Held in New York. The 19th Exposition of Chemical Industries will be held in Madison Square Garden, New York, N. Y., during the first week in December 1943, with admission by invitation, and registration only for executives, chemists, chemical engineers, plant managers, and staff personnel directly associated with industries having a chemical interest. A significant exhibit will be one sponsored by the Alien Property Custodian of the United States Government of the complete library of former enemy-controlled patents, now available for use under license by American manufacturers in chemical, electrical, and mechanical fields. In addition to issuing patent licenses, the Office of the Custodian soon will begin to sell to American investors enemy-owned businesses worth billions of dollars. The properties to be transferred range from the multi-million dollar Aniline and Film Corporation to delicatessens and cobblers' shops. Inventories of these properties will be made available by the Custodian's office.

JOINT ACTIVITIES

New Standard for Graphs Issued

Recommendations, intended to result in more legible and understandable graphs, based on past practice or on scientifically established principles are made to authors of technical material by the new "American Standard for Engineering and Scientific Graphs for Publications," recently issued by the American Standards Association.

Besides presenting well-grounded reasons for the rules and guides formulated, helpful illustrations and examples are provided. Starting from the standpoint of the function a graph should fulfill and emphasizing the distinction between graphs which will reproduce well and those which may be best for other display or demonstration purposes, the standard reaches the conclusions that: a graph should complement not duplicate textual material; exaggerated sizes or lines which distract from the text should be avoided; consideration must be given to the optics of lettering (numerical ratios are given); and disproportionate enlarging of any one factor in a graph should be avoided. Other pitfalls, obvious to the printer but not always to an author, are pointed out. Copies may be obtained from the American Standards Association, 29 West 39th Street, New York 18, N. Y., at 75 cents per copy.

Automatic Pilot Improves Precision Bombing

The supersensitivity of the electronically controlled automatic pilot, developed by Minneapolis-Honeywell Regulator Company and used on all United States Army bombers since 1941, holds a plane to its course despite cross currents, wind variation, and blast from exploding antiaircraft shells. Besides supplying a steady platform for high-altitude precision bombing, the device permits of variable installation, so that the plane can be flown from two or three different points. Although the manual control cables connecting to the rudder and elevators were severed in a mid-air collision with a German Messerschmitt, this Boeing Flying Fortress was flown safely home on the autopilot because the control circuit motors of the electronic system were located far in the tail and were not damaged in the crash

EDUCATION . . .

Northwestern Forms Advisory Committee

Eleven representatives of business, industry, and technical education comprise the new advisory committee on the development of the Technological Institute of Northwestern University, President Franklyn B. Snyder announced.

Charles F. Kettering (F '14) vice-president of General Motors Corporation, Dayton, Ohio, who was selected as adviser to the Technological Institute by its founder, Walter P. Murphy, in 1939, is committee chairman.

From the field of technical education the four committee members are: K. T. Compton (F '31), Massachusetts Institute of Technology, Cambridge; R. A. Millikan (HM '33), California Institute of Technology, Pasadena; W. E. Wickenden (F '39), Case School of Applied Science, Cleveland, Ohio; and R. E. Doherty (F '39), Carnegie Institute of Technology, Pittsburgh, Pa. The remaining six members from business and industry are: Henry J. Kaiser, shipbuilder and industrialist; Juan Terry Trippe, president of Pan American Airways; James S. Knowlson, president of Stewart Warner Corporation; General Robert E. Wood, chairman of the board, Sears Roebuck and Company; Ralph Budd, president of the Burlington Railroad; and Paul E. Klopstag, president of the Central Scientific Company.

The new committee will be concerned primarily with the postwar program and activities of the institute. It will counsel the institute on its relations with industry, future theoretical and applied research programs, curricula in engineering and

science, new techniques in engineering education, and engineering prospects in the United States and abroad. For further details about the Technological Institute see the July 1942 issue of *Electrical Engineering*, page 385.

LETTERS TO THE EDITOR

INSTITUTE members and subscribers are invited to contribute to these columns expressions of opinion dealing with published articles, technical papers, or other subjects of general professional interest. While endeavoring to publish as many letters as possible, Electrical Engineering reserves the right to publish them in whole or in part or to reject them entirely. Statements in letters are expressly understood to be made by the writers. Publication here in no wise constitutes endorsement or recognition by the AIEE. All letters submitted for publication should be typewritten, double-spaced, not carbon copies. Any illustrations should be submitted in duplicate, one copy an inked drawing without lettering, the other lettered. Captions should be supplied for all illustrations.

Current-Transformer Excitation Under Transient Conditions

To the Editor:

I wish to thank Mr. Etches for making available the corrections to our paper, "Current-Transformer Excitation Under Transient Conditions," by D. E. Marshall and P. O. Langguth, published in AIEE *Transactions*, volume 48, October 1929, pages 1464–74. We have checked the *Transactions* copy of the original paper and find the errors to be as pointed out and the corrected equations as given by Mr. Etches to be correct. (*EE, May '43, p. 228*).

In the interests of complete accuracy, we wish to point out that the symbol T as used in the corrections appears in two kinds of type. This is not mathematically significant.

D. E. MARSHALL (M '33)

(Sections engineer, electronics engineering department, Westinghouse Electric and Manufacturing Company, Bloomfield, N. J.)

Deriving the Parameters of Filters

To the Editor:

It is very disappointing to have such authorities as Schelkunoff,[1] Slater,[2] and Terman[3] publish the well-written books they recently have and still base their derivation of the parameters of the ladder-type filter on the full section as done by Campbell,[4] the inventor of this type of filter, when the half section is so superior pedagogically.

Consider the network shown in Figure 1. Here Z is the impedance of the series branch and Y the admittance of the shunt branch of the half section. Z_1 and Y_1 are the mid-series image impedance and mid-shunt image admittances, respectively. Then the impedance of the network looking to the right at 1–1 is

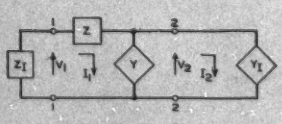


Figure 1

$$Z_1 = Z + \frac{1}{Y + Y_1} \qquad (1)$$

and the admittance of the network looking to the left at 2–2 is

$$Y_1 = Y + \frac{1}{Z + Z_1} \qquad (2)$$

Substituting the value of Y_1 from equation 2 in equation 1 gives the mid-series image impedance

$$Z_1 = \sqrt{\frac{Z}{Y}}\sqrt{YZ+1} \qquad (3)$$

Substituting the value of Z_1 from equation 1 in equation 2 gives the mid-shunt image admittance

$$Y_1 = \sqrt{\frac{Y}{Z}}\sqrt{YZ+1} \qquad (4)$$

The latter also may be written directly from symmetry.

These expressions are simpler to derive and remember than the usual expressions, namely,[5]

$$Z_{11}(=Z_1) = \sqrt{Z_1 Z_2 + Z_1^2/4} \qquad (5)$$

and

$$Z_{12}\left(=\frac{1}{Y_1}\right) = \sqrt{\frac{Z_1 Z_2}{1 + Z_1/4Z_2}} \qquad (6)$$

Also the expression for the image-transfer constant, θ, is simpler for the half section or L section

$$\sinh\theta = \sqrt{ZY}$$

than the older expression for the II or T section[6]

$$\sinh\theta_{H/2} = \sqrt{Z_1/4Z_2}$$

If the development is based on the L section, the II and T sections follow directly by putting two L sections back to back. But by using the L section the factors of two and one half which occur in the design equations for the simple low-pass, high-pass, and confluent band-pass filters are eliminated. For the low- and high-pass filters, the two arms are resonant at the cutoff frequencies, and the impedance of either at the cutoff frequency is equal to the load resistance of the filter. The transformation of the frequency that changes the low-pass filter into the confluent band-pass filter preserves this relationship.

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2. Microwave Transmission (book), J. C. Slater. McGraw-Hill Book Company, Inc., New York, N. Y., 1942.

3. Radio Engineers Handbook (book), F. E. Terman. McGraw-Hill Book Company, Inc., New York, N. Y., 1943 (Network Theory Filters, and Equalizers, Part III, preprinted in *Proceedings* Institute of Radio Engineers, 31, June 1943, pages 288–302).

4. Physical Theory of the Electric Wave Filter, G. A. Campbell. *Bell System Technical Journal*, 1, April 1922, pages 1–32.

5. Transmission Networks and Wave Filters (book), T. E. Shea. D. Van Nostrand Company, New York, N. Y., 1929. Page 222.

6. Reference 3, page 288.

G. R. BURROWS (M '33)

(Radio research engineering department, Bell Telephone Laboratories, Inc., New York, N. Y.)

Electrical Engineering in the War

To the Editor:

Have been over here for about a year now, with the Army Engineer Corps, and it has been a busy year, as you know. Modern warfare is about half engineering, of one kind or another, and we get all kinds and then some.

Electrical engineers are well represented over here but it seems to me the Army needs about twice as many electrical engineers and trained electricians as it now has.

Now that the preliminary African "bout" is over we will have to get ready for the "main event." We will need all the electrical equipment that American electrical manufacturers can produce, and they sure are producing some beautiful stuff. It has to meet tough conditions—and it does.

Maybe we will get it down some day to where you just push a button—and Bingo—another big hole in the map!

A LIEUTENANT COLONEL, UNITED STATES ARMY

24-Hour Time Designation

To the Editor:

I should like to second Mr. Sidney Withington's proposal for a 24-hour time designation in this country. Naturally, those who have utilized that system in Europe can better appreciate its advantages than those who have not had an opportunity to try it. Since the latter constitute the great majority, considerable effort un-

doubtedly will be required to overcome their "conservatism."

In this case, the "conservatism" probably should be classified as mental rather than economic and so not of "the same kind which has inhibited adoption of the metric system of weights and measures . . . . ." As I recall it, a very comprehensive investigation a few years ago indicated it would be decidedly uneconomic to change our machine tools from English to metric units. Perhaps that change might be reconsidered after the war.

I am interested also in another time-designation proposal which does not conflict in any way with Mr. Withington's. In 1936, and again in 1942, I proposed over the radio that the proper standard-time designation be substituted for the daylight-saving-time designation utilized in each standard time zone during the "fast-time" period. Thus, the term "eastern standard time" would be substituted for "central daylight-saving time" in the central time zone. In our eastern time zone, the term "Atlantic standard time" would be substituted for "eastern daylight-saving time."

This proposal usually appeals to scientifically minded individuals who understand the advantages of using well-standardized terms whenever possible. However, these advantages are not so apparent to the majority. Also, to them "Atlantic standard time undoubtedly is as unfamiliar as "24-hour time." Thus, unfamiliarity with one of the proposed terms, "conservatism" or mental inertia, lack of suitable promotion, and now the war, have prevented so far the adoption of the standard-time designations.

I hope Mr. Withington will be more successful with his proposal.

C. T. WELLER (M '21)

(Electrical engineer, General Electric Company, Schenectady, N. Y.)

NEW BOOKS • • •

The following new books are among those recently received from the publishers. Books designated ESL are available at the Engineering Societies Library; these and thousands of other technical books may be borrowed from the library by mail by AIEE members. The Institute assumes no responsibility for statements made in the following summaries, information for which is taken from the prefaces of the books. All inquiries relating to the purchase of any book reviewed in these columns should be addressed to the publisher of the book in question.

History of the Latin-American Nations. By W. S. Robertson. Third edition. D. Appleton-Century Company, Inc., New York, N. Y.; and London, England, 1943. 560 pages, 6½ by 9½ inches, $4.

Written for the general reader as well as for college and university classes, this history attempts to satisfy the growing interest of both groups in the countries of South and Central America and Mexico. In his presentation the author stresses the differences which give individuality to the political units composing Latin America. Separate treatment is accorded each country's struggle for independence and its subsequent history. However their common source in 15th century Spanish civilization and the prehistoric Indian civilizations is given consideration. Colonial culture and institutions are surveyed. In the discussion of the modern governments emphasis is laid on political and constitutional changes. The field of Latin America's relations with Great Britain, other European powers, and the United States, of which the author has made a special study, also is covered. Chapter references have been added to the present edition, and maps have been provided where necessary.

Reference Data for Radio Engineers. Federal Telephone and Radio Corporation, 67 Broad Street, New York, N. Y., 1943. 200 pages, 5¾ by 8¼ inches, $1; orders of 12 or more, 75 cents per copy.

This radio reference handbook is an attempt to provide for the requirements of the engineer as well as the radio technician. Compactly presenting more of the fundamentals of radio than are offered by the usual handbook, it should be useful both in the laboratory and the field. The material is compiled under the following general headings: general engineering tables, engineering and material data, audio and radio design, rectifiers, vacuum tubes and amplifiers, telephone transmission, radio-frequency transmission lines, radio propagation and antennas, noise and noise measurement, nonsinusoidal wave forms. There are also sections of mathematical formulas and tables.

Machine Shop Yearbook and Production Engineers' Manual. 2nd edition. Edited by H. C. Town. Paul Elek, Africa House, Kingsway, London, W.C.2, England, 1943. 497 pages, illustrations, etc., 8½ by 5½ inches, cloth, 30s. 10d., or abroad 31s. 6d. (ESL.)

Late developments in production, management, and design are here presented in convenient form for reference and study. Four special articles are included: on electrical-control gear for machine tools, on optical instruments in engineering, on centerless grinding, and on the direct hydraulic system. Machine-tool construction and operation are discussed at length, with descriptions of representative British machine tools. The periodical literature of 1942 is represented by abridged articles of important publications on production and shopwork.

Formulas for Stress and Strain. By R. J. Roark. 2nd edition. McGraw-Hill Book Company, Inc., New York, N. Y., and London, England, 1943. 366 pages, diagrams, etc., 9 by 6 inches, cloth, $4. (ESL.)

Intended as a reference book for designers, this book offers a compact summary of the formulas, facts, and principles relating to strength of materials. Part 1 treats of definitions and symbols. Part 2 states general principles and describes methods of stress analysis and the behavior of material under stress. Part 3, which occupies most of the book, discusses the behavior of structural elements under various conditions of loading and gives extensive tables of formulas for the calculation of stress, strain, and strength. Bibliographies accompany the chapters. The new edition has been enlarged.

Manual of Firemanship, Part I. Great Britain, Home Office (Fire Service Department). His Majesty's Stationery Office, London, England, 1943. 250 pages, illustrations, etc., 8½ by 5½ inches, paper, 2s. 6d. (obtainable from British Information Services, 30 Rockefeller Plaza, New York, N. Y., 75 cents). (ESL.)

This book is the first section of a proposed seven-part work which is intended to be a comprehensive textbook and reference work for fire fighters. The present installment discusses the theory of fire fighting and the equipment. The theory of combustion, methods of extinguishing fires, hose, hose fittings, ladders, ropes, hand pumps, chemical extinguishers and foams, and apparatus for breathing and resuscitation are discussed. Much practical information is given.

Theory and Practice of Heat Engines. By H. R. Grundy. Longmans, Green and Company, London, England; New York, N. Y.; and Toronto, Ont.; 1942. 723 pages, illustrations, etc., 9 by 5½ inches, cloth, $6.25. (ESL.)

This textbook offers a course covering steam generators, reciprocating steam engines, steam turbines, and internal-combustion engines in one volume. It is intended to cover the practical side of the subject and the accompanying theory to a stage from which an easy step may be made to more specialized books. The book is profusely illustrated with drawings, and the text is clear and readable. Considerable attention is given to historical development. A good picture of modern practice, especially British, is provided.

Drying and Dehydration of Foods. By H. W. von Loesecke. Reinhold Publishing Corporation, New York, N. Y., 1943. 302 pages, illustrations, etc., 9½ by 6 inches, cloth, $4.25. (ESL.)

This book, which aims to offer a compilation of the latest practical information on its subject, is the work of one who has had considerable experience in research work on dehydration. It presents a general outline of procedures and practices in commercial use. Types of dehydrators, the dehydration of various classes of foods, plant sanitation, costs, the nutritive value of dried foods, packing, storage, methods of analysis, and the reconstitution of dehydrated foods are considered. A glossary and a list of patents are appended.

Radio Engineers' Handbook. By F. E. Terman. McGraw-Hill Book Company,

Inc., New York, N. Y., and London, England, 1943. 1019 pages, illustrations, etc., 9 by 6 inches, leather, $6. (ESL.)

This handbook brings together, in form for reference use, the body of engineering knowledge that is the basis of radio and electronics. It presents, in organized form, the more important contributions to the art that have appeared in the technical articles, over 2,000 in number, that were reviewed in preparing it. Extensive references provide access to much pertinent literature. As the book is essentially a one-man job, the viewpoint is consistent throughout and gaps and duplications are avoided.

Engineering Mechanics. By F. L. Singer. Harper and Brothers, New York, N. Y., and London, England, 1943. 482 pages, diagrams, etc., 9½ by 6 inches, cloth, $4. (ESL.)

This is a textbook that aims to present the fundamentals of the subject in a manner that will result in thorough understanding and permanent possession of them. Toward this aim, emphasis is centered on a physical understanding of the basic operations, rather than on routine rules. Equations are interpreted in terms of their geometrical equivalents, wherever possible. Analytic methods have been emphasized without neglecting graphic ones. Numerous illustrative problems are explained to show the applications of the theory.

Engineer's Manual of English. By W. O. Sypherd, A. M. Fountain and S. Brown. Revised edition. Scott, Foresman and Company, Chicago, Ill.; Atlanta, Ga.; Dallas, Tex.; New York, N. Y.; 1943. 503 pages, diagrams, etc., 8 by 5 inches, cloth, $2.50. (ESL.)

This compact volume is intended as a textbook in English composition for students and as a reference book on usage for engineers. After the technique that underlies all good writing has been presented, the writing of letters, reports, articles, bulletins, and specifications is discussed in detail with numerous examples. The new edition has been revised thoroughly and much improved. It will be found useful by all readers.

Metals and Alloys Data Book. By S. L. Hoyt. Reinhold Publishing Corporation, New York, N. Y., 1943. 334 pages, illustrations, etc., 10½ by 7 inches, cloth, $4.75. (ESL.)

Mr. Hoyt has performed a task of great value, and the result will be most useful to metallurgists and engineers. It contains in compact usable form, carefully selected values for the physical and engineering properties of the metals and alloys of commercial importance. The wrought, cast, and stainless steels, cast irons, heat-resistant and corrosion-resistant casting alloys and nonferrous alloys are covered in detail. The data are chiefly presented in tables with brief comment.

Physics of Metals. By F. Seitz. McGraw-Hill Book Company, Inc., New York, N. Y., and London, England, 1943. 330 pages, diagrams, etc., 8½ by 5½ inches, fabrikoid, $4. (ESL.)

This work is based on an evening lecture course given to practicing metallurgists with a limited knowledge of physics. The treatment is entirely nonmathematical. The developments of recent years are discussed, including the structure of metals, the factors that determine the stability of alloys, the theory of plasticity in metals, diffusion in metals, the theory of iron–carbon alloys, and the electron theory of solids and its applications to cohesion, magnetism, and conductivity.

Introduction to Circuit Analysis. By A. R. Knight and G. H. Fett. Harper and Brothers, New York, N. Y., and London, England, 1943. 447 pages, diagrams, etc., 9½ by 6 inches, cloth, $4. (ESL.)

This book is intended as a text for the initial and basic course in electrical engineering. The first five chapters provide an understanding of the necessary fundamental electrical and magnetic laws, and serve as a review of previous study. Chapter 6 is a detailed study of the step-by-step solution of electric circuits. Succeeding chapters develop the electric-circuit theory and include a discussion of electric-transient theory from the physical point of view.

Rewinding Data for Direct-Current Armatures. By G. A. Van Brunt and A. C. Roe. 2nd edition. McGraw-Hill Book Company, Inc., New York, N. Y., and London, England, 1943. 277 pages, illustrations, etc., 9½ by 6 inches, cloth, $2.50. (ESL.)

Detailed practical directions are given for rewinding all types of these armatures and for taking and recording the necessary data. The new edition has been revised and enlarged. New data include such recent developments as the use of glass fiber insulation, drying and baking by infrared heating, and the introduction of new insulating varnishes.

Aircraft Navigation. Part I: Theory, by H. Stewart and A. Nichols. Part II: Practice, by S. A. Walling and J. C. Hill. Macmillan Company, New York, N. Y.; University Press, Cambridge, England, 1943. 146 pages, illustrations, etc., 8½ by 5½ inches, cloth, $2. (ESL.)

Beginning students of air navigation will find here a concise introduction to the subjects that they must master. Star identification, map reading, position finding, meteorology, and other theoretical matters are explained, and a large number of practical problems provided. The text is the work of British authorities, but has been revised for American use.

Handbook of Plastics. By H. R. Simonds and C. Ellis, assisted by M. H. Bigelow. D. Van Nostrand Company, New York, N. Y., 1943. 1082 pages, illustrations, etc., 9½ by 6½ inches, cloth, $10. (ESL.)

This volume aims to meet a desire for a comprehensive reference work that would treat the details of the subject in one volume. It presents, in nine sections, the fundamental basis and technology of the plastics industry, including the physical and chemical properties of plastics, their production, manufacture, finishing, and applications. A section on plant practice is included. There is a list of trade-marks and trade names, and a bibliography.

Physical Chemistry. By F. H. MacDougall. Revised edition. The Macmillan Company, New York, N. Y., 1943. 722 pages, diagrams, etc., 9 by 5½ inches, cloth, $4.25. (ESL.)

This is an introductory text which aims to provide a sound working knowledge of the subject for students of chemistry and chemical engineering. The new edition has been revised to include changes in the accepted value of fundamental constants and certain additions to the text.

PAMPHLETS . . .

The following recently issued pamphlets may be of interest to readers of "Electrical Engineering." All inquiries should be addressed to the issuers.

Community Action for Post-War Jobs and Profits. United States Department of Commerce, Washington, D. C., copies sent on request.

War Winning Suggestions in the War Production Drive. War Production Board, Washington, D. C., 61 pages.

Cooling System: Cleaning, Flushing, Rust Preventions, and Antifreeze. Prepared by the Society of Automotive Engineers, Inc., Office of Defense Transportation, 1147 New Post Office Building, Washington, D. C., 25 pages.

Bridgeport Condenser Tube Manual. Bridgeport Brass Company, Bridgeport 2, Conn., 112 pages.

Trail Blazer to Radionics and Reference Guide to Ultrahigh Frequencies. By E. Kelsey, Zenith Radio Corporation, 680 North Michigan Avenue, Chicago 11, Ill., 56 pages, no charge, copies available upon requests for use in schools.

Recreation—a Resource of War. The Division of Recreation, Federal Security Agency, Social Security Building, Washington 25, D. C., 8 pages, no charge.

Products and Priorities. Issued every four weeks by the War Production Board, Washington, D. C., 13-week subscription, $2.

List of Inspected Appliances Relating to Accident Hazard, Automotive Equipment, Burglary Protection. Underwriters Laboratories, Inc., 161 Sixth Avenue, New York 13, N. Y., 77 pages.

Electricity in the Chemical Industry. General Electric Company, Schenectady, N. Y., 40 pages.

Economical and Permanent Construction with Pressure-Treated Wood. Koppers Company, Wood Preserving Division, Pittsburgh, Pa., 26 pages, no charge.

TRANSACTIONS SECTION

Preprint of Corresponding Pages From the Current Annual AIEE Transactions Volume

Any discussion of these papers will appear in the December 1943 Supplement to Electrical Engineering—Transactions Section

Operation of Nonsalient-Pole-Type Generators Supplying a Rectifier Load

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IT has been recognized that the presence of harmonic currents in the supply circuit are a source of additional heating in the generators supplying a rectifier load, particularly where a six-phase rectifier is the total load. Robert Pohl has presented papers on this subject, and from his work has concluded that an appreciable reduction in the rating of turbine generators is required when the rectifiers are connected for 6-phase and 12-phase operation.[1,2] Experience in this country with turbine generators operating with rectifier loads indicated that the reduction factors presented by Doctor Pohl were too large, so a test program was carried out to determine the practical limits of such loads. The test results and experience both indicate that for 12-phase operation and above, the effect on the supply system is very small and in most cases may be neglected.

Any harmonic current flowing in the stator winding of a generator increases the temperature rise of the stator winding and surrounding parts. Also, these harmonics establish a magnetomotive force which results in currents flowing in the surface of the rotor, adding to the rotor heating. It can be shown that some harmonics rotate backward, and some harmonics rotate forward with respect to the fundamental.[3] Because it rotates against the rotation of the rotor, the magnetomotive force set up by the fifth harmonic results in a sixth harmonic on the surface of the rotor. Since the rotation of the seventh harmonic is in the same direction as that of the rotor, it also results in a sixth harmonic on the rotor surface. These two magnetomotive forces, rotating in opposite directions, result in a pulsating field on some axis of the rotor. Likewise, another pulsating field of 12 times normal frequency is set up by the action of the 11th and 13th harmonics. The harmonics, up to the 25th, present in the stator and rotor are shown in Table I.

Paper 43-114, recommended by the AIEE committees on electrical machinery and electronics for presentation at the AIEE national technical meeting, Cleveland, Ohio, June 21-25, 1943. Manuscript submitted April 15, 1943; made available for printing May 24, 1943.

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The authors acknowledge the assistance of J. H. Cox and L. A. Kilgore.

Tests

The temperature tests were made on a 1,250-kva 2,300-volt three-phase, 60-cycle 3,600-rpm turbine generator supplying a 600-volt ignitron rectifier connected for double three-phase operation, as shown in Figure 2. Double three-phase is a form of six-phase operation. The regulation of the rectifier was approximately ten per cent. That is, the impedance of the lines, transformer, and rectifier was of such a value that there was a drop in voltage equal to ten per cent of the normal voltage when full generator load was applied. In addition, the lines were not supplied from what might be considered an infinite system, but instead, from a single generator. The subtransient reactance of this generator was approximately 11 per cent. The importance of this fact and its effect on the magnitude of harmonic currents will be shown later. The generator was operated at approximately full kilovolt-amperes for four temperature runs, with the temperature of the stator winding being measured by detector, and the temperature of the rotor winding being measured by the increase in resistance. Oscillograms of the wave form were taken during each run, in order to obtain the magnitude of the harmonic currents to be used in subsequent calculations. After each test, the rotor was inspected to determine whether burning had occurred, either between the wedges and the teeth, or at the joints between the retaining rings and the rotor body. There was, however, no evidence of burning on any of the runs, indicating that excessive heating did not occur under the loading conditions of the test. Table II shows the results of the tests. In order to obtain the additional temperature rise of the stator and rotor windings, preliminary temperature runs were made at zero load and full voltage; full kilovolt-amperes and 90 per cent power factor; and full kilovolt-amperes and zero per cent power factor. Using the results of these tests, it was possible to determine what the temperatures would have been if the harmonic currents had not been included in the load current. The additional temperature rise shown in the tables is the difference between the measured temperature rise and the normal temperature rise for that particular load.

Rotor Heating

In order to calculate the heating of the rotor, the loss can be determined by the use of the negative-sequence resistance of

Table I. Harmonics Present in Stator and Rotor

	Stator Harmonics		Resultant Rotor Harmonics		
Order of Harmonic	6-Phase Connection	12-Phase Connection	6-Phase Connection	12-Phase Connection	Rotation of Harmonics
1	1	1			Forward
3					
5	5		6		Backward
7	7		6		Forward
9					
11	11	11	12	12	Backward
13	13	13	12	12	Forward
15					
17	17		18		Backward
19	19		18		Forward
21					
23	23	23	24	24	Backward
25	25	25	24	24	Forward

Table IIA. Generator Test Results—Temperature Runs

Rectifier Connected for Double Three-Phase Operation

Phase Delay (Degrees)	Voltage	Current	Power Factor	Stator Temperature Rise (Degrees Centigrade)		Rotor Temperature Rise (Degrees Centigrade)		Ambient Temperature (Degrees Centigrade)
				Total	Additional	Total	Additional	
0	2300	297	90	40	2.6	79.1	19.1	28.8
14.1	2300	302	89.3	40.8	2.8	86	22	29.7
24.7	2300	296	83.5	42.5	5.1	93.1	22.1	25.4
30.4	2300	295	81.5	44	6.6	95.5	25.5	28.8

Table IIB. Generator Test Results—Per Cent Harmonic Currents in Supply Circuit

Rectifier Connected for Double Three-Phase Operation

Order of Harmonic	Phase Delay (Degrees)			
	0	14.1	24.7	30.4
1	99.0	99.5	98.26	98.3
3	0.10	1.76	0.99	1.80
5	11.80	13.50	15.30	15.30
7	6.72	7.24	5.60	6.63
9	0.11	1.29	0.48	2.05
11	2.41	4.10	5.77	5.38
13	1.75	2.92	3.03	3.39
17	1.03	1.10	2.94	2.61
19	1.18	0.53	1.59	2.28
23	0.33	1.17	1.59	1.15
25	0.76	0.89	0.86	1.02

the rotor. A description of the test method for obtaining this value is given in the appendix. A minor correction in the value of resistance must be made, since the loss varies as the 1.8 power of the negative-sequence current for turbine generators.[4] Since the fifth and seventh harmonics result in two sixth-harmonic waves rotating in opposite directions on the surface of the rotor, the current to be used in calculating the sixth-harmonic loss can be taken as the sum of the fifth and seventh harmonics. This figure of loss must be multiplied by three, for the three phases, and by two, because at 120 cycles only one-half the rotor loss is $I_2^2R_2$, the other half being supplied through the shaft. The sum of the harmonic currents gives the maximum loss for the complete periphery of the rotor, but the actual loss is an average between the points of maximum and minimum loss. Thus, the maximum loss must be reduced by a factor, K_a, in order to obtain the average loss. The factor K_a may be obtained from Figure 5, once the ratio of the two harmonic currents is known. The derivation of the curve in Figure 5 is given in the appendix.

In obtaining the temperature rise, a factor, K_p, of 0.11 watt per degree centigrade per square inch of rotor surface, neglecting the surface of the retaining rings, was used for this particular peripheral speed. An air velocity of one-half the peripheral speed of the rotor was assumed. Since the temperature rise was measured on the rotor winding instead of the rotor surface, it was necessary to take into account the portion of the rotor winding which was affected by the additional loss on the rotor surface. The construction of the rotor for this machine was such that the ventilation of the portion of the coils beneath the retaining rings was very good, and it was assumed that all the extra heat in these sections of the winding was dissipated to the air passing over the end turns of the rotor winding, leaving only the slot portion of the winding to be affected by the additional loss on the surface of the rotor. On this rotor, the slot portion of the winding was 54 per cent of the mean turn, and this value was used for the winding ventilation factor, K_w. This factor may vary widely, depending on the physical proportions of the rotor, as well as the amount of ventilation on the end turns of the rotor winding.

The temperature rise of the rotor winding caused by the harmonic currents may be calculated for the various even-numbered harmonics from the following equation, using the currents of order $n-1$ and $n+1$, where n is the order of the harmonic on the surface of the rotor.

$$\text{Temperature rise} = 2\times 3\times \frac{K_w}{K_s\times S}\times \Sigma K_a(I_{n-1}+I_{n+1})^2(R_1-R_l)\sqrt{\frac{f}{120}}$$

where

K_a = average loss factor
K_w = winding ventilation factor
K_s = heat-dissipation factor
S = rotor surface = ($\pi\times$rotor diameter$\times$ core length)

Table III compares the calculated and test values for the four temperature runs.

Figure 1. Oscillogram showing wave form in generator field and armature circuits

Double three-phase ignitron operating with 30.4 degrees phase delay. 1,250-kva turbo-generator, 2,300 volts, three phase, 60 cycles, 3,600 rpm

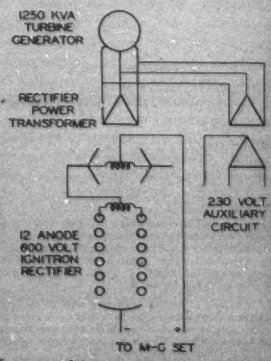


Figure 2. Schematic diagram of test circuit

Table III. Additional Temperature Rise of Rotor Winding

Reduction Factors Applying to This Machine Connected to Double Three-Phase Ignitron

Phase Delay (Degrees)	Additional Rise (Degrees Centigrade)		Load Reduction Factor	
	Test	Calculated	Test	Calculated
0	19.1	19.3	1.0	1.0
14.1	22	27.6	0.995	0.95
24.7	22.1	32.3	0.92	0.85
30.4	25.5	32.2	0.9	0.85

The reduction in load to maintain not more than 85 degrees centigrade rotor temperature rise was calculated for each load condition and is given in Table III as a reduction factor. To determine this value, the additional temperature rise of the rotor caused by the harmonic currents was varied as the square of the load current, and the rise caused by the field current was calculated from the saturation curves of the machine. The two components were added by trial until the proper figure was obtained. It should be noted that these reduction factors apply only to this particular machine, and they cannot be generalized to cover all machines.

Figure 3 (above). 1,250-kva turbine generator on test

Figure 4 (right). 12-anode ignitron on test

Stator Heating

The calculation of the heating of the stator winding is complicated further by the fact that the temperatures by detector are affected not only by the I^2R loss as determined by the eddy factor, but also by the heating of the stator parts, and by the extra loss on the surface of the rotor. It has been suggested that the load on the stator should be reduced according to the square root of the ratio of the normal loss to the loss with rectifier load as calculated by the use of the eddy factor alone, and neglecting any effect of core loss or rotor loss.[1] This method has been followed in the calculations for Table IV. These calculations have been made for the average loss, using the average eddy factor and for the maximum loss in the top strand. The effective eddy factor, $K_{eff.}$, equals $\Sigma I^2K_e/\Sigma I^2$, and the reduction, R, in load equals $\sqrt{K_e}$ (fundamental)$/K_{eff.}$ The reduction factors, R and R', for the average and top strands, respectively, may be compared with the reduction factors from the measured additional temperature rise by inspection of Table IV.

The stator temperature rise on the normal full-load test was 38 degrees centigrade, which is considerably below the maximum value of 60 degrees centigrade rise. While this stator had considerable temperature margin, it was thought worth while to prepare a series of load reduction factors based on maintaining the full-load temperature rise of 38 degrees centigrade with various rectifier loads. It was assumed that the permissible load varied as the square root of the ratio of the temperature rise under normal load to the temperature rise with rectifier load. The reduction factors for this machine alone are given in Table IV.

Table IV. Additional Temperature Rise of Stator Winding

Reduction Factors Applying to This Machine Connected to Double Three-Phase Ignitron

Phase Delay (Degrees)	Additional Rise From Test (Degrees Centigrade)	Reduction Factor From Test	Calculated Reduction Factor	
			Average	Top Strand
0	2.6	0.966	0.963	0.95
14.1	2.8	0.965	0.94	0.917
24.7	5.1	0.937	0.915	0.895
30.4	6.6	0.922	0.907	0.887

12-Phase Operation

The foregoing tests and calculations were all on the basis of the rectifier operating with a double three-phase connection. If the connection had been 12 phase, the magnitude of the 5th, 7th, 17th, and 19th harmonics would have been reduced, with some improvement in power factor. In order to compare the performance with double 3-phase and 12-phase connections, the calculations have been made, eliminating the 5th,

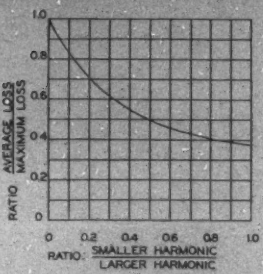


Figure 5. Values of rotor loss factor K_a

7th, 17th, and 19th harmonics, and assuming the magnitudes of the others were unchanged. The calculated reduction factor for the stator winding was 0.96 compared with 0.907 for the condition of 30.4 degrees phase delay. The calculated additional temperature rise for the rotor winding was approximately six degrees for the 30.4-degree delay condition compared to 25.5 degrees for the double three-phase connection. Considering the improvement in power factor and the lower temperature rise, the rotor heating for the assumed conditions will not affect the permissible loading.

Conclusions

From these tests and calculations, and from previous studies of rectifier operation, the following conclusions may be drawn:

1. A rectifier load is the source of harmonic currents in the supply system. These harmonic currents cause extra heating in the stator and rotor of a generator, and, in some cases, may require a reduction in rating of supplying generators.

2. The order of the harmonic currents is affected by the number of phases of rectifier operation, and their magnitude is affected by the voltage reduction or phase delay, and the impedance of the complete system.[5,6,7] The lowest-order harmonic current which exists in the supply circuit is $P-1$, where P is the number of phases of rectifier operation. With a rectifier operating with a 12-phase connection, the additional heating of the generator will be slight, and with a number of phases higher than 12, the additional heating will be negligible. The magnitude of the harmonic currents is reduced with a reduction in degrees ignitor delay and an increase in system impedance.

3. For a given load, the rotor heating is more pronounced than the stator heating, but operation at a relatively high power factor will introduce some margin in the rotor heating. Under certain conditions of operation the stator heating becomes the limiting factor.

4. It is not possible to state any definite rule for the reduction in rectifier load necessary in order to keep generator temperatures within recognized limits, because the extra heating is affected by the physical proportions of the machine, as well as the loading conditions. It is possible, however, to determine the magnitude of the harmonic currents,[5,6] once the loading conditions are known. The extra heating and any necessary reduction in load can be determined by the generator designer, using the methods outlined in this discussion.

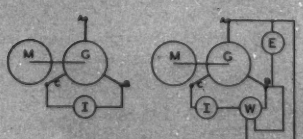


Figure 6. Generator connections for obtaining negative-sequence resistance

Appendix A

Method of Obtaining Negative-Sequence Resistance

The negative-sequence resistance may be determined by either one of two methods.[4,8]

For Figure 6a, drive the generator at synchronous speed.

$$R_2 = \frac{3(P - P_{FRW})}{2I^2}$$

where

P = shaft input in watts
P_{FRW} = friction and windage loss in watts
I = phase current

For Figure 6b, drive the generator at synchronous speed.

$$\text{Power factor} = \frac{P}{E \times I} = \cos\theta$$

$$Z_2 = 3\frac{E}{I}$$

$$R_2 = \frac{E}{3}\frac{\sin}{I}\theta$$

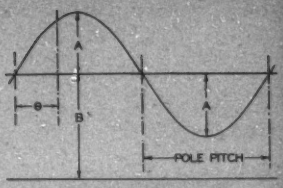
where

P = power in watts
E = line-to-line voltage
I = phase current

It should be noted that both of these methods require a sustained, single-phase short circuit, and care should be taken to see that the rotor is not overheated.

Appendix B

Since the fifth harmonic current rotates against the direction of rotation of the rotor, it generates a sixth harmonic current in the rotor surface. The seventh harmonic current rotates with the rotor, also generating a sixth harmonic current in the rotor surface, but the direction of rotation is opposite to that caused by the fifth harmonic current. Thus, there are two points of maximum loss and two points of minimum loss, with a sinusoidal distribution between. This relationship holds for any pair of harmonic currents which generate any particular frequency in the rotor surface. The distribution is shown in Figure 7, where A is the smaller of the two harmonic currents and B is the larger.



"A" IS THE SMALLER OF TWO HARMONIC CURRENTS

Figure 7. Resultant current distribution around rotor periphery

Let average loss around periphery equal L and angle around periphery equal θ, then

$$L = \frac{1}{2\pi}\int_0^{2\pi}(B + A\sin\theta)^2 d\theta$$

$$= \frac{1}{2\pi}\left[B^2\theta - 2AB\cos\theta + A^2\left(\frac{\theta}{2} - \frac{\sin 2\theta}{4}\right)\right]_0^{2\pi}$$

$$= B^2 + \frac{A^2}{2}$$

Figure 5 gives the ratio of the average loss to the maximum loss for any ratio of the two harmonic currents.

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Rotating Regulator for Arc Furnaces

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Synopsis: Increased production of steel alloy for the war effort has brought about a wider use of electric-arc furnaces, and with this improvements have been made in automatic regulation of electrode position.

The Rototrol regulator described in this paper is of the rotating type which controls electrode position as determined by response to current in the electrode and voltage between the electrode and the furnace shell. Features and performance of a typical installation are illustrated.

AUTOMATIC adjustment of electrode position has always been used as a means of controlling the power input to steel-melting arc furnaces. This is necessary because the charge melts and flows away from the electrode so that the electrode must be lowered to maintain the arc. The scrap being melted frequently falls against the electrode, making withdrawal necessary to remove the short circuit. Furthermore, adjustment is necessary to allow for natural electrode consumption.

In addition to this the arc is a pure resistance load, and changing its length by adjustment of the electrode position gives a simple and satisfactory method of controlling the current.

The early arc-furnace regulator was a simple current-operated device. The electrode current in each phase was supplied from a current transformer to the coil of the regulator element. The pull of this coil was then balanced against a spring, and the operation of the regulator contacts caused the hoist motor to run in either direction to raise or lower the electrode as the current varied from some predetermined value. Figure 1 shows a typical arc furnace for steel melting. The hoist motors as shown are connected through a wire cable and drum sheave so as to lower and raise the electrode masts from which the electrodes are supported. This mechanical system is varied somewhat with different designs of furnace, but the electrical problem is simply one of automatic control, suitable for reversing and braking the electrode motor.

Current regulation was generally unsatisfactory when precise control was necessary, chiefly because the restraining force of the spring had a constant value. The variations of the current in the circuit are rapid at times, and the mechanical movement of the electrode is slow. Therefore, the position of the electrode responded not to instantaneous but to an average value of current variation. Furthermore, a three-phase system of currents in an electric furnace is complex. The furnace charge is a ground which connects through three continually shifting phase arcs to the potential supplied by the transformer. It is clear that the currents in the regulator elements are not independent but rather are interdependent; the value in any phase at a given time is determined by conditions in the other two phases, as well as by the length of the arc in that particular phase.

As is well known, the voltage drop across the arc will increase as the current is decreased and vice versa. In practice this characteristic can be modified by inserting additional reactance in the circuit. In fact, a sufficient value of reactance must be present in the circuit to maintain stability, so that the combination of arc resistance and circuit impedance will have a positive impedance characteristic over the operating zone. These theoretical requirements of the arc-furnace circuit have been frequently discussed in other articles on the subject and are well known. It should not be forgotten, however, that a considerable part of the circuit reactance in the case of the larger furnaces is in the secondary leads, and, therefore, such furnaces require no additional reactance for stable operation.

It is readily understood that, when the varying pull of the coil or other regulating device which is proportional to current in the electrode, is matched against a restraining force that is proportional to the voltage drop across the arc, the utmost sensitivity to changes in arc length is obtained in the regulator. While this sensitivity may not be so important when the furnace is reducing the cold scrap to a molten bath, it is of great importance when this molten bath is being refined.

The development of the art over a period of years showed that this principle of regulation was correct. It was natural that further development should look for improvements of the controlling scheme for the motor which for many years had been a constant-potential d-c, reversing control combined with dynamic braking.

Quite independently of the arc-furnace industry, however, new methods of regulation had been introduced in other industrial applications where regulated control of motors to adjust for speed, tension, rate of acceleration, and so forth, were desired. These methods for the

Figure 1. Representative arc furnace for steel melting

Paper 43-96, recommended by the AIEE committee on electrochemistry and electrometallurgy for presentation at the AIEE national technical meeting, Cleveland, Ohio, June 21-25, 1943. Manuscript submitted April 8, 1943; made available for printing May 20, 1943.

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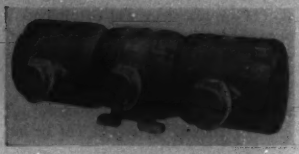

Figure 2. Typical unit including Rototrol, a-c motor, and d-c generator

most part were based on a different means of operating the motor in response to the regulating element. Instead of using a constant-potential control, adjustable-voltage control of the motors was used and has been found very satisfactory. An independent source of d-c voltage is required and is usually supplied by a motor generator set. If the exciter for this generator is supplied with suitable control fields, a complete regulating system is formed in which the regulating element is a part of the power supply for the electrode motors.

The Rototrol regulator was first applied to an automatic welding head in 1928. A few years later it was applied to the large elevators in Radio City and, since then, has found wide use in many industrial applications. It is the heart of the adjustable-voltage planer drive and has been proved in service over a period of several years. Other applications include paper-mill drives, electric shovels, mine sweepers, skip hoists, bomb spinners, and machine tools, some of which provide speed ranges as high as 120 to 1.

The rotating-type arc-furnace regulator was thus a natural development prompted by the use of similar regulators in other applications. It has been favorably received chiefly because the direct tie between the generator and the motor eliminates all contactors in the motor circuits.

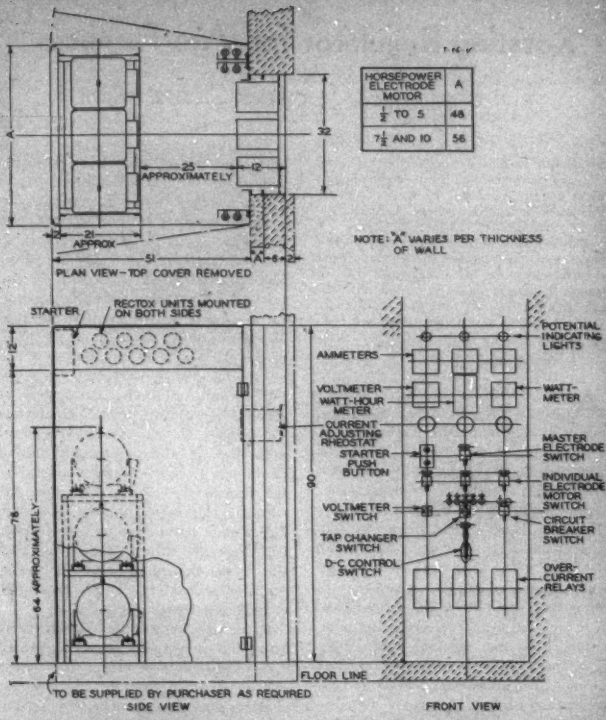

Figure 4. Metal-enclosed Rototrol arc-furnace control and regulator unit

The Rototrol is essentially a small d-c machine similar in both construction and theory of operation to the standard d-c generator of like size. It is driven by a standard squirrel-cage induction motor as part of the motor generator set, Figure 2. The magnetic circuit is excited by a number of field windings, and the machine functions entirely through the interaction of these fields. The field coils constitute the input of the device, while the output is obtained from the armature circuit. The principal field windings include:

1. A control field which serves as a reference against which the quantity to be regulated is compared.
2. A control field which measures the quantity to be regulated.
3. A self-energizing field connected either in series or in shunt with the armature.

For a high degree of accuracy, the various control fields should have complete control over the regulating element without supplying any of the magnetomotive force necessary to generate power in its own output circuit. The self-energizing field circuit is designed so that its resistance line will be coincident with the air-gap line of the no-load saturation curve. This results in a high degree of amplification since an extremely small change of power in the control fields is ample to change the output over its full range.

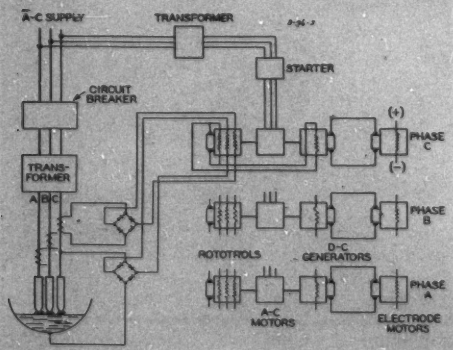

Figure 3. Elementary diagram of arc-furnace regulating system

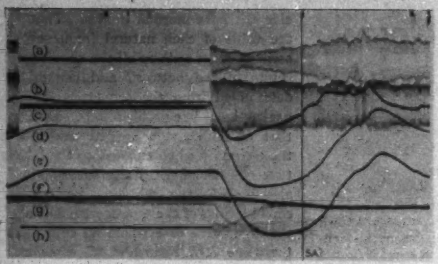

Figure 5. Oscillogram showing electrical performance of regulator during the melt-down period

(a). Electrode current to Rototrol control field
(b). Rototrol armature volts
(c). A-c volts to Rototrol control field
(d). Motor armature volts
(e). Motor speed
(f). Electrode position indicator
(g). Motor armature current
(h). Electrode current

This output is applied to the field of the constant-speed direct-connected generator, which supplies power to the electrode motors.

The speed of response of the system comprising the arc-furnace regulating element and the power-supplying generator must be carefully co-ordinated with the acceleration characteristics of the electrode motor in order to obtain the maximum rate of acceleration permissible without exceeding the commutating ability of the electrode motor. Acceleration of the electrode motor is influenced by the system inertia, the friction load, and the torque developed by the motor. For instance, a three-horsepower equipment with a system WR^2 at the motor shaft of 1.5 pound-feet squared, a friction load of two-thirds full-load torque and a maximum motor torque of 1.5 times rated will accelerate to rated speed in about one half of a second.

The speed of response of the regulating element depends on the ratio of inductance to resistance for each field, the mutual induction between the fields, and the relative ratios of turns and time constants of the various fields. It is particularly important that time-constant and relative-turn ratio of the self-energizing field be correctly proportioned. Assuming a three-field machine, the differential equation of load voltage e will be:

$$e = k_1 i_1 - k_2 i_2 + k_3 i_3 = i_3 r_3 + L_3 \frac{di_3}{dt} + M_{23} \frac{di_2}{dt} + M_{13} \frac{di_1}{dt}$$

where

k_1, k_2, k_3 are machine constants with various field turns.
i_1, i_2, i_3 are the respective field currents.
r_3 is the self-energizing field resistance.
L_3 is the self-energizing field inductance.
N_{23}, M_{13} are the mutual inductances between fields 2 and 3, and between fields 1 and 3.

By combining this with the equations for other field voltages, the differential equation of voltage build-up in the output circuit can be obtained. Solution of equations of this type are of the forms:

$$e = A_1 \epsilon^{m_1 t} + A_2 \epsilon^{m_2 t} + A_3 \epsilon^{m_3 t} + B$$

where the A's, m's, and B are constants depending on L, R, and M.

By proper proportion of the field circuits, any reasonable speed of response as required for electrode control can be obtained. Optimum performance is obtained when the speed of response of the electrical system is co-ordinated with acceleration characteristics of the mechanical system.

Figure 3 shows an elementary diagram of the regulating system. The current control field of the regulating element is energized from a dry-type rectifier which is in turn connected to a current transformer in the electrode circuit. The potential control field is energized in a similar manner from the voltage between each electrode and the shell of the furnace. In practice, when the breaker in closed voltage is applied to the potential control field which causes the generator voltage to build up in the direction to lower the electrodes. When the first electrode strikes the metal, the voltage drops to zero causing the motor to stop. When a second electrode strikes the metal, a current flows causing the current control field to become energized which acts to raise the electrode thus establishing an arc. As the arc is lengthened, its voltage increases and the current decreases until a balance is established between the potential and current control fields. The

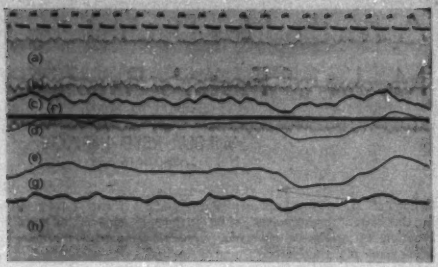

Figure 6. Oscillogram showing electrical performance of regulator during the refining period

(a). Electrode current to Rototrol control field
(b). Rototrol armature volts
(c). A-c volts to Rototrol control field
(d). Motor armature volts
(e). Motor speed
(f). Electrode position indicator
(g). Motor armature current
(h). Electrode current

third electrode is controlled in a similar manner.

As the charge melts and flows away, as the electrodes burn off, and as the scrap falls against the electrodes, the balance between the control fields is continually being disturbed. The Rototrol changes the generator voltage to position the electrodes to maintain the balance between arc voltage and current. This arrangement of the control field circuits corresponds to the accepted principle of regulation used successfully for many years in the balanced-beam type of regulator.

Provision is made for controlling the electrodes manually, either individually or in a group. This facilitates handling of the electrodes during charging, pouring, changing electrodes and so forth.

The wide range of current adjustment required is obtained by means of a rheostat shunting the current transformer. This method is used, since it maintains the same sensitivity for all current settings.

Figure 4 shows the arrangement of equipment in a single metal-enclosed unit. The front panel is arranged for setting into the wall of the furnace vault in the usual manner. Hinged side panels are used on the rear of the unit in order to provide maximum accessibility to the rotating equipment as well as to the panel mounted apparatus. A bolted rear plate is provided so that any one or all of the motor generator sets can be readily removed for inspection or maintenance. Enclosed machines with ball bearings are

A Method for Determining the Normal Modes of Foster's Reactance Networks

WILBUR REED LePAGE
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Synopsis: A method is presented for finding the zeros of the impedance or admittance function of a Foster reactance network. More generally, the method is one of finding the zeros of a rational function having alternate zeros and poles, all of which are simple, if the poles are known; or of finding the poles if the zeros are known. The method consists of writing the function as a sum of partial fractions and replacing all but two of the fractions, depending on the zero to be found, by a constant and solving the resulting quadratic equation. In this way an upper and lower bound of a zero may be found, and, if need be, the method may be applied repeatedly to give a pair of bounds which will be as close to the required zero as necessary. The method has particular value if the rational function is the impedance or admittance function of one of Foster's reactance networks, since these functions are obtained directly from the networks as sums of partial fractions of the form $A_n/(B_n^2-\omega^2)$. Hence, the zeros may be obtained without reducing the function to the polynomial form. The new method may not always be shorter in application than other known methods, but its advantage lies in the facility with which an upper and lower bound of the required zero may be found and in the possibility of dealing with the partial-fraction form of the impedance or admittance function.

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Statement of the Problem

THE two generalized networks of Figure 1 are Foster's canonic forms, which are of particular importance because either one is a possible representation of any reactance network.[1] They are forms in which the normal modes of oscillation are placed in evidence: for Figure 1a they coincide with the network meshes,[2] and for Figure 1b, which is the dual[1] of Figure 1a, the normal modes coincide with the network nodes. This means that if Figure 1a is excited by a voltage, or Figure 1b by a current, the response frequencies are merely those of the isolated sections. However, if the excitations of these networks are, respectively, current and voltage, they no longer have nodes or meshes which coincide with the normal modes. That is, the value of each natural frequency of oscillation depends on all the circuit constants of the network and cannot be determined from the properties of any one section. The problem to be treated is that of finding the normal modes for these circuits when exposed to the latter type of excitation. These solutions will also include the solutions for certain combinations of these networks, and also the dissipative case where all coils have the same R/L ratio and all capacitors have the same G/C ratio. The method will be illustrated in terms of the voltage excitation of Figure 1b, but with the application of the principles of duality[2] it applies also to the current excitation of Figure 1a. There are known methods for finding these normal modes, but under the special conditions of the circuits considered here the method to be introduced will provide good approximations with a minimum of effort.

Determination of the Normal Modes

On a mesh basis none of the possible meshes of Figure 1b satisfy the necessary conditions to make them coincide with the normal modes,[2] and if there are no such meshes the normal modes, regardless of the actual point of insertion of the disturbing voltage, are the values of p for which

$$Z(p)=0 \qquad (1)$$

used exclusively to eliminate periodic oiling, also to keep abrasive dust out of bearings. Individual motor generator sets having rugged construction and ample safety factors are employed. Should a failure of any unpredictable kind occur, the heat can be continued with two electrodes on automatic control and a spare set placed in service quickly.

The equipment is made so far as possible in one unit so that the various parts can be protected from dirt and physical damage. This also permits factory assembly and complete test, up to the operation of the electrode motors. A minimum of external connections and erection time is thus required.

Figure 5 is an oscillogram showing typical operation of the furnace during the melt-down period. This demonstrates the high speed of the electrodes. Unsustained sudden variations in current cause no extra action or undue wear on the equipment, but sustained changes cause immediate response. It will be noted that the electrode can be withdrawn at relatively high speed when a cave-in takes place. In case of abnormal unbalance between current and voltage in the arc, the equipment is able to perform its function with the minimum number of outages.

The start of the film shows a loss of voltage and current. The motor comes to rest in about one half of a second and remains at rest until the arc is re-established. In this case, the current was low and the Rototrol voltage immediately started rising in a direction to cause the electrode to be lowered. The motor started one seventh of a second after the change was initiated. This delay was due to the electrical and mechanical inertia of the system. The motor was accelerated rapidly to full speed, and, as the current approached the regulated value, the motor speed was diminished. At point 5-*A* there was a marked rise in current and the electrode motor was decelerated to zero speed and accelerated to one-third speed in the raise direction. It should be appreciated that during the melt-down period, electrical conditions in the furnace change rapidly, necessitating more or less continual electrode adjustment. This film covers a period of about ten seconds.

Figure 6 is an oscillogram showing the refining period. Here, relatively small changes in current take place, and consequently only small movement of electrodes is required. Because of the inertia of the electrical system, sudden unsustained variations do not cause movement of the electrodes.

Operating experience has shown that the Rototrol regulator combines the necessary degree of sensitivity, amplification, speeds of response, and stability required for arc-furnace operation. This regulator is particularly successful during melt-down periods when cave-ins frequently occur because the high speed withdrawal of the electrodes prevents breaker tripping because of sustained overload.

where p is the usual generalized angular velocity and $Z(p)$ is the impedance function of the network.[4]

For the network in question,

$$Z(p) = p\left(L_0 + \sum_{n=1}^{N} \frac{A_n}{B_n^2 + p^2}\right) \tag{2}$$

where

$$\left.\begin{aligned} A_n &= 1/C_n && \text{(a)} \\ B_n &= 1/\sqrt{L_n C_n} && \text{(b)} \end{aligned}\right\} \tag{3}$$

When there is a series capacitor, as shown in Figure 1b, it is a special case of the parallel combination for which the corresponding $B=0$, and is therefore included in the summation.

For the reactance network the values of p which satisfy equation 1 are pure imaginaries, and accordingly we are interested only in purely imaginary values of p. Therefore, it is convenient to let

$$p = j\omega \tag{4}$$

and

$$Z(p) = Z(j\omega) = j\omega\left(L_0 + \sum_{n=1}^{N} \frac{A_n}{B_n^2 - \omega^2}\right) \tag{5}$$

It follows from the separation property of zeros and poles[1] of equation 5 that there will be a root of equation 1 between any two adjacent values of B_n. Let the values of B_n be arranged as an increasing sequence, with increasing subscripts, and choose the subscripts on the roots so that

$$B_1 < \omega_1 < B_1 < \omega_2 < \ldots < B_{k-1} < \omega_k < B_k < \ldots < \omega_N \tag{6}$$

All B's will be different because it is assumed that Figure 1b is reduced to its simplest form. The solution is obtained by solving

$$L_0 + \phi(\omega) = 0 \tag{7}$$

where

$$\phi(\omega) = \sum_{n=1}^{N} \frac{A_n}{B_n^2 - \omega^2} \tag{8}$$

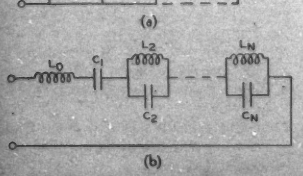


Figure 1. Foster's reactance networks

which contains all the roots except the trivial root $\omega=0$ which occurs if $B_1 \neq 0$ and which has been factored out.

This is made clearer by the typical plot of $\phi(\omega)$, as shown in Figure 2. The function closely resembles a reactance function, since the latter is $\omega\phi(\omega)$. The intersections of these curves with the horizontal line $-L_0$ are the required roots. They are located symmetrically about the vertical axis, and therefore it is necessary to consider only the positive roots.

There are two procedures to be followed, depending on whether $1 \leq k \leq N-1$ or $k=N$.

CASE 1. $1 \leq k \leq N-1$

The root ω_k lies in the interval

$$B_k < \omega_k < B_{k+1} \tag{9}$$

and with this knowledge we can separate out the two terms of $\phi(\omega)$ which have poles nearest to ω_k and approximate the remaining terms by a term which will be a constant. Equation 7 becomes

$$\frac{A_k}{B_k^2 - \omega^2} + \frac{A_{k+1}}{B_{k+1}^2 - \omega^2} = \psi(k, \omega) = W(k) \tag{10}$$

which serves to define $\psi(k, \omega)$, and where W is a constant. The solution of equation 10 is

$$\left.\begin{aligned} \omega^2 &= \frac{1}{2W}\left[F(k) + G(k)\right], && W \neq 0 \\ &= \frac{B_{k+1}^2 A_k + B_k^2 A_{k+1}}{A_{k+1} + A_k}, && W = 0 \end{aligned}\right\} 1 \leq k \leq N-1 \quad \begin{matrix} \text{(a)} \\ \text{(b)} \end{matrix} \tag{11}$$

where

$$F(k) = W(B_{k+1}^2 + B_k^2) - (A_{k+1} + A_k) \qquad \text{(c)}$$

and

$$G(k) = \sqrt{(A_{k+1} + A_k)^2 - 2W(B_{k+1}^2 - B_k^2)^2(A_{k+1} - A_k) + W^2(B_{k+1}^2 - B_k^2)^2} \qquad \text{(d)}$$

The form of $\psi(k, \omega)$ is shown in Figure 3, and it is seen from this that there may be an extraneous root outside of the interval B_k to B_{k+1}. However, equation 11 is written in such a form as to always give a root within the required interval. In speaking of a root of equation 10 it will always be understood that it is the root given by equation 11. It is evident from the form of $\psi(k, \omega)$ that there will always be a root, regardless of the value of W. The problem is now one of finding suitable values of W. To do this we write equation 7 as

$$\left.\begin{aligned} &\psi(k, \omega) = S(k, \omega) && \text{(a)} \\ &\text{where} \\ &S(k, \omega) = -L_0 - \sum_{\substack{n=1 \\ n \neq k,\, k+1}}^{N} \frac{A_n}{B_n^2 - \omega^2} && \text{(b)} \end{aligned}\right\} \tag{12}$$

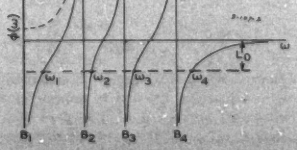


Figure 2. Plot of $\phi(\omega)$ versus ω to show the locations of the roots. Shown for N = 4

$S(k, \omega)$ is shown in Figure 3, and it is apparent that in the interval between B_k and B_{k+1}, $\psi(k, \omega)$ is continuous and always increasing, and that $S(k, \omega)$ is continuous, always decreasing, and is bounded. Thus, if ω_p is any value, $B_k \leq \omega_p \leq B_{k+1}$, and we define

$$W = S(k, \omega_p) \tag{13}$$

there will be a solution of equation 10 which we will call ω_q and which will have the following properties:

$$\text{if } \begin{Bmatrix} \omega_p > \omega_k \\ \omega_p = \omega_k \\ \omega_p < \omega_k \end{Bmatrix} \text{ then } \begin{Bmatrix} \omega_q < \omega_k \\ \omega_q = \omega_k \\ \omega_q > \omega_k \end{Bmatrix} \tag{14}$$

The properties of $\psi(k, \omega)$ and $S(k, \omega)$ also show that if $B_k \leq \omega_p' < \omega_p \leq B_{k+1}$, and ω_q' is the root corresponding to ω_p', as given by equations 11 and 13, then

$$B_k < \omega_q < \omega_q' < B_{k+1} \tag{15}$$

In view of these relations we will find it expedient to define

$$\left.\begin{aligned} W_1(k) &= S(k, B_k) && \text{(a)} \\ W_2(k) &= S(k, B_{k+1}) && \text{(b)} \end{aligned}\right\} \tag{16}$$

and let the corresponding roots of equation 10 be $\bar{\omega}_k$ and ω_k, respectively. From relations 9, 14, and 15 it follows that

$$B_k < \omega_k < \bar{\omega}_k < B_{k+1} \tag{17}$$

and we have determined upper and lower bounds of ω_k which are closer than B_k and B_{k+1}. If this approximation is not sufficient, one may use ω_k and $\bar{\omega}_k$ in place of B_k and B_{k+1}, respectively, and determine two new roots, $\bar{\omega}_k'$ and ω_k'.

This process may be repeated as many times as required. To be more specific, define

$$\left.\begin{aligned} W_1^{(s)}(k) &= S[k, \varphi_k^{(s-1)}] \\ W_2^{(s)}(k) &= S[k, \bar{\omega}_k^{(s-1)}] \end{aligned}\right\} \quad s \geq 1 \qquad \begin{matrix}(a)\\(b)\end{matrix} \qquad (18)$$

and let $\bar{\omega}_k^{(s)}$ and $\varphi_k^{(s)}$ be the roots of equation 10 using equations 18a and b, respectively, for W. Consider the case $s=1$. From relations 15 and 17 it follows that $\bar{\omega}_k' < \bar{\omega}_k$ and $\varphi_k' > \varphi_k$, and from relations 14 and 17 we obtain the relations $\bar{\omega}_k' \geq \omega_k$ and $\varphi_k' < \omega_k$. Hence,

$$B_k < \varphi_k < \varphi_k' < \omega_k < \bar{\omega}_k' < \bar{\omega}_k < B_{k+1} \qquad (19)$$

It is obvious that this reasoning may be continued, leading to the pair of sequences

$$\left.\begin{aligned} &\bar{\omega}_k > \bar{\omega}_k' > \bar{\omega}_k'' > \ldots > \bar{\omega}_k^{(s-1)} > \bar{\omega}_k^{(s)} > \ldots > \omega_k \\ &\varphi_k < \varphi_k' < \varphi_k'' < \ldots < \varphi_k^{(s-1)} < \varphi_k^{(s)} < \ldots < \omega_k \end{aligned}\right\} \qquad (20)$$

Observe that relation 20 contains twice as many values as required to obtain a given approximation. For example, if $\bar{\omega}_k$ is found one can immediately find φ_k', and then $\bar{\omega}_k''$, and so forth. Similarly, φ_k could be used as the starting point, and thus, either of the following pairs of sequences may be used:

$$\left.\begin{aligned} &\bar{\omega}_k > \bar{\omega}_k'' > \ldots > \bar{\omega}_k^{(s-2)} > \bar{\omega}_k^{(s)} > \ldots > \omega_k \\ &\varphi_k' < \varphi_k''' < \ldots < \varphi_k^{(s-1)} < \varphi_k^{(s+1)} < \ldots < \omega_k \end{aligned}\right\} \quad (a)$$

or

$$\left.\begin{aligned} &\bar{\omega}_k' > \bar{\omega}_k''' > \ldots > \bar{\omega}_k^{(s-1)} > \bar{\omega}_k^{(s+1)} > \ldots > \omega_k \\ &\varphi_k < \varphi_k'' < \ldots < \varphi_k^{(s-2)} < \varphi_k^{(s)} < \ldots < \omega_k \end{aligned}\right\} \quad (b) \qquad (21)$$

CASE 2. $k=N$

This case requires special treatment because there is no pole of $\phi(\omega)$ beyond B_N, and ω_N is in the range

$$B_N < \omega_N < \infty \qquad (22)$$

In contrast to the previous practice, it is not possible to keep two terms, having poles on opposite sides of ω_N, in their exact form and replace the remainder of $\phi(\omega)$ by an approximation. One could, therefore, keep only one term, $A_N \div (B_N^2 - \omega^2)$, as the exact term. However, since the solution can be given explicitly if two exact terms are used, a more accurate approximation will be obtained by also using the term $A_{N-1}/(B_{N-1}^2 - \omega^2)$.

One is lead to attempt to approximate the other terms by a constant, as was done in case 1. That is, we will seek a suitable value of W to make the solution of

$$\psi(N-1, \omega) = W(N) \qquad (23)$$

approximate ω_N. $\psi(N-1, \omega)$ is shown in Figure 4 from which it is seen that for equation 23 to have a solution it is necessary that $W < 0$. Assuming this to be true the solution is

$$\left.\begin{aligned} \omega^2 &= \frac{1}{2W}[F(N) - G(N)], \quad W<0 \quad (a) \\ &\text{where} \\ F(N) &= W(B_N^2 + B_{N-1}^2) - (A_N + A_{N-1}) \quad (b) \\ &\text{and} \\ G(N) &= \sqrt{\begin{matrix}(A_N + A_{N-1})^2 - 2W(B_N^2 - \\ B_{N-1}^2)^2(A_N - A_{N-1}) + \\ W^2(B_N^2 - B_{N-1}^2)^2\end{matrix}} \quad (c) \end{aligned}\right\} \qquad (24)$$

This is written in such a way as to give the solution which is greater than B_N. The root given by equation 24 will henceforth be spoken of as the root of equation 23. Continuing, as for case 1, we write equation 7 as

$$\psi(N-1, \omega) = S(N-1, \omega) \qquad (25)$$

and examine $S(N-1, \omega)$ in the interval of ω for which it may serve as a value of W. For $\omega > B_N$, $S(N-1, \omega)$ is continuous and always decreasing, with increasing ω, and becomes less than zero at some point, ω_t, as indicated in Figure 4. This point may lie on either side of B_N. If ω_t is the larger of ω_r and B_N, and if W is defined as

$$W = S(N-1, \omega_t) \qquad (26)$$

where $\omega_s < \omega_t < \infty$, then there will be a solution of equation 23 for this value of W. Let this solution be ω_u. From the properties of $\psi(N-1, \omega)$ and $S(N-1, \omega)$ one may conclude that

$$\text{if } \begin{Bmatrix} \omega_t > \omega_N \\ \omega_t = \omega_N \\ \omega_t < \omega_N \end{Bmatrix} \text{ then } \begin{Bmatrix} \omega_u < \omega_N \\ \omega_u = \omega_N \\ \omega_u > \omega_N \end{Bmatrix} \qquad (27)$$

and if $\omega_s \leqq \omega_t' < \omega_t \leqq \infty$ and ω_u' is the root corresponding to ω_t', as given by equations 26 and 24, then

$$\omega_t < \omega_u < \omega_u' < \infty \qquad (28)$$

The procedure to be used in obtaining a solution depends on the position of ω_r relative to B_N. For the first case, assume $S(N-1, B_N) < 0$, which is equivalent to the condition $\omega_r < B_N$. This is similar to case 1 and accordingly we define

$$\left.\begin{aligned} W_1(N) &= S(N-1, B_N) \quad (a) \\ W_2(N) &= S(N-1, \infty) = -L_0 \quad (b) \end{aligned}\right\} \qquad (29)$$

The corresponding roots obtained by using equations 29a and b, respectively, will be $\bar{\omega}_N$ and φ_N, and in view of relations 22, 27, and 28 they will satisfy the inequality

$$B_N < \varphi_N < \omega_N < \bar{\omega}_N \qquad (30)$$

Closer approximations may be obtained, exactly as in case 1, by defining

$$\left.\begin{aligned} W_1^{(s)}(N) &= S[N-1, \varphi_N^{(s-1)}] \\ W_2^{(s)}(N) &= S[N-1, \bar{\omega}_N^{(s-1)}] \end{aligned}\right\} \quad s \geq 1 \qquad \begin{matrix}(a)\\(b)\end{matrix} \qquad (31)$$

and $\bar{\omega}_N^{(s)}$ and $\varphi_N^{(s)}$ as the roots of equation 23 using, respectively, equations 31a and b for W. For $s=1$, in consequence of relations 28 and 30, we have $\bar{\omega}_N' < \bar{\omega}_N$ and $\varphi_N' > \varphi_N$ and from relations 27 and 30, $\bar{\omega}_N' > \omega_N$ and $\varphi_N' < \omega_N$. Therefore we may write the inequality

$$B_N < \varphi_N < \varphi_N' < \omega_N < \bar{\omega}_N' < \bar{\omega}_N \qquad (32)$$

and by extending this repeatedly there results the pair of sequences,

$$\left.\begin{aligned} &\bar{\omega}_N > \bar{\omega}_N' > \bar{\omega}_N'' > \ldots > \bar{\omega}_N^{(s-1)} > \bar{\omega}_N^{(s)} > \ldots > \omega_N \\ &\varphi_N < \varphi_N' < \varphi_N'' < \ldots < \varphi_N^{(s-1)} < \varphi_N^{(s)} < \ldots < \omega_N \end{aligned}\right\} \qquad (33)$$

from which either of the two following pairs may be selected for computation:

$$\left.\begin{aligned} &\bar{\omega}_N > \bar{\omega}_N'' > \ldots > \bar{\omega}_N^{(s-2)} > \bar{\omega}_N^{(s)} > \ldots > \omega_N \\ &\varphi_N' < \varphi_N''' < \ldots < \varphi_N^{(s-1)} < \varphi_N^{(s+1)} < \ldots < \omega_N \end{aligned}\right\} \quad (a)$$

$$\left.\begin{aligned} &\bar{\omega}_N' > \bar{\omega}_N''' > \ldots > \bar{\omega}_N^{(s-1)} > \bar{\omega}_N^{(s+1)} > \ldots > \omega_N \\ &\varphi_N < \varphi_N'' < \ldots < \varphi_N^{(s-2)} < \varphi_N^{(s)} < \ldots < \omega_N \end{aligned}\right\} \quad (b) \qquad (34)$$

With the introduction of the sequences 34b there is some relaxing of the original condition, that $W_1(N) < 0$. To use these sequences it is necessary only to have $W_1'(N) < 0$, which is equivalent to $\varphi_N > \omega_r$.

If $W_1'(N) \geqq 0$, an upper bound of ω_N may be found by another method which consists of obtaining a root of

$$\psi(N-1, \omega) = -L_0 - \sum_{n=1}^{N-2} \frac{A_n}{B_{N-1}^2 - \omega^2} \qquad (35)$$

It is easy to see that equation 35 has a root, by writing it as

$$\left.\begin{aligned} &\frac{A_{N-1}'}{B_{N-1}^2 - \omega^2} + \frac{A_N}{B_N^2 - \omega^2} = -L_0 \quad (a) \\ &\text{where} \\ &A_{N-1}' = \sum_{n=1}^{N-1} A_n \quad (b) \end{aligned}\right\} \qquad (36)$$

Let this root be designated by $\bar{\omega}_N^*$, and observe that, if $\omega > B_N$, then

$$-\sum_{n=1}^{N-2} \frac{A_n}{B_{N-1}^2 - \omega^2} > -\sum_{n=1}^{N-2} \frac{A_n}{B_n^2 - \omega^2} \qquad (37)$$

From this, and the fact that $\psi(N-1, \omega)$ is increasing with increasing ω, it may be concluded that

$$\bar{\omega}_N^* > \omega_N \qquad (38)$$

Thus $\tilde{\omega}_N^*$, an upper bound of ω_N, has been found by a method which is applicable in all cases.

It is of interest to note, parenthetically, that if $W_1'(N)<0$ then $\tilde{\omega}_N^*$ and $\tilde{\omega}_N'$ can both be found, and if there is much difference between them it may be worth the extra computation required to know which is the closer to ω_N and therefore which one may be most profitably used as the basis for future computations of the sequences 34. It is possible to know which is the better approximation by computing $\tilde{\omega}_N^*$ and then either also computing ω_N' and comparing directly with $\tilde{\omega}_N^*$, or comparing $S(N-1, \varphi_N)$ with

$$-L_0-\sum_{n=1}^{N-1} A_n/(B_{N-1}^2-\tilde{\omega}_N^{*2}) \tag{}$$

If the former is larger, then $\tilde{\omega}_N'>\tilde{\omega}_N^*$, and vice versa.

To return to the case where $W_1'(N)\gtrless 0$, $\tilde{\omega}_N^*$ having been found, it may be used to define

$$W_2^*(N)=S(N-1, \tilde{\omega}_N^*) \tag{39}$$

If the root of equation 23, when $W_2^*(N)$ is used, is φ_N^*, it follows from relations 27 and 38 that $\varphi_N^*<\omega_N$. Also, $S(N-1, \tilde{\omega}_N^*)>S(N-1, \infty)$ and therefore, from the increasing property of $\psi(N-1, \omega)$,

$$\varphi_N<\varphi_N^*<\omega_N \tag{40}$$

Although $\varphi_N<\omega_r$ it is possible that $\varphi_N^*>\omega_r$, in which event φ_N^* is a possible starting point for the sequences 34, as a replacement for either B_N or φ_N. Whether this condition is fulfilled may be checked by observing if $S(N-1, \omega_N^*)$ is less than zero, this being the necessary and sufficient condition to make $\varphi_N^*>\omega_r$.

If this attempt at finding an improved upper bound, by first seeking a lower bound which is greater than ω_r, is not successful, the following procedure may be used. Arbitrarily choose a value, ω_N^*, such that

$$\left.\begin{array}{ll} \varphi_N^*<\omega_N^*<\tilde{\omega}_N^* & \text{(a)} \\ \text{and} & \\ S(N-1, \omega_N^*)<0 & \text{(b)} \end{array}\right\} \tag{41}$$

If ω_N^* is less than ω_N, it may be used as B_N or φ_N in forming the sequences 34. To find whether this is true use $S(N-1, \omega_N^*)$ as W in equation 23 and call the resulting root $\omega_N^{*\prime}$. From relation 27, if

$$\left.\begin{array}{ll} \omega_N^{*\prime}>\omega_N^* & \text{(a)} \\ \text{then} & \\ \omega_N^*<\omega_N & \text{(b)} \end{array}\right\} \tag{42}$$

Also, from relation 27, if

$$\left.\begin{array}{ll} \omega_N^{*\prime}<\omega_N^* & \text{(a)} \\ \text{then} & \\ \omega_N^{*\prime}<\omega_N & \text{(b)} \\ \text{and if} & \\ S(N-1, \omega_N^{*\prime})<0 & \text{(c)} \end{array}\right\} \tag{43}$$

$\omega_N^{*\prime}$ may be used as B_N or ω_N in relation 34. Thus, there are two possibilities: if relation 42*a* is true the search for a lower bound is completed, and the same conclusion follows if relation 43*a* and *c* are both true. However, if relation 43*a* is true but 43*c* is not true then another, smaller, value will have to be assumed for ω_N^*.

Application to Other Circuits

In Figure 5 two circuits are shown, to which this method of determining the

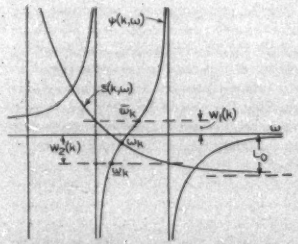


Figure 3. Properties of the functions involved in finding all the roots except the largest

normal modes is applicable. Consider Figure 5b, with a current excitation, a voltage excitation being no different than the previous problem and of no further interest. The normal modes will be the values of p which make

$$Y(p)=0 \tag{44}$$

From the form of the circuit it is apparent that

$$Y(p)=\frac{Z_A(p)+Z_B(p)}{Z_A(p)Z_B(p)} \tag{45}$$

and hence, if p_k is a root of

$$Z_A(p)+Z_B(p)=0 \tag{46}$$

it is also a root of equation 44 unless $Z_A(p_k)=Z_B(p_k)=0$. The roots of equation 46 can be found by the method which has been presented. Likewise, for Figure 5*a* the normal modes are the roots of

$$Y_A(p)+Y_B(p)=0 \tag{47}$$

and, as has been indicated, the formal solution of equation 47 is the same as the solution of equation 46.

All of these networks can be treated equally well if all coils have the same R/L ratio and all capacitors the same G/C ratio. The general case of this is treated by Guillemin[5] who shows that if

$$\alpha=R/2L \quad \text{and} \quad \beta=G/2C \tag{48}$$

then, for roots of $Z(p)=0$, we obtain

$$\left.\begin{array}{ll} p_k=-(\alpha+\beta)\pm j\omega_k & \text{(a)} \\ \text{where} & \\ \omega_k=\sqrt{g_k^2-(\alpha-\beta)^2} & \text{(b)} \end{array}\right\} \tag{49}$$

and where g_k is the value that p_k would have if there were no dissipation.

Application to Other Rational Functions

An impedance or admittance function of a reactance network is a special rational function which has everywhere a positive slope and, consequently, alternating poles and zeros all of which are simple. The poles come in pairs located symmetrically about the point $\omega=0$, and the residue at one of the poles is the negative of the residue at its mate. This makes it possible, for such a function, to combine the terms representing the two poles of a pair into one term and only treat the function for $\omega>0$. The fact that the zeros come in pairs, located symmetrically about the point $\omega=0$, is indicated by equations 10 and 24 because there the zeros are given in terms of ω^2. In the general case of a rational function having alternate poles and zeros, all of which are simple, the same procedure may be used to find upper and lower bounds of the zeros, but without the possibility of combining terms. If the poles and residues are known the approximate zero will be a solution of an equation of the form

$$\frac{A_k}{B_k-\omega}+\frac{A_{k+1}}{B_{k+1}-\omega}=W \tag{50}$$

where W is defined in similarity with equations 12 and 13 but where the summation must be over all the poles except B_k and B_{k+1}. Equation 50 is a quadratic in ω, and its solution is given by equations 11, but with ω^2 replaced by ω. The treatment for the greatest and smallest zeros will be similar to that given under case 2, with the aforementioned modifications.

It should be pointed out that it is necessary to know only the locations of the poles since the residues may be found by explicit methods.[6] Also, if the locations of the zeros of a function are known, the poles may be found by applying the method to the reciprocal of the function.

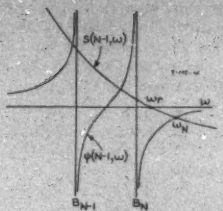
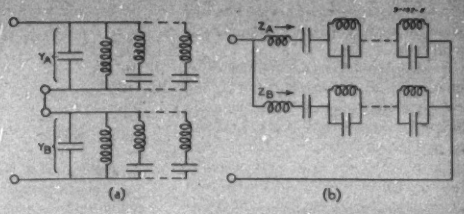


Figure 4. Properties of the functions involved in finding the largest root

Figure 5. Combinations of the reactance networks to which the method is applicable



Therefore, this method may be used to find the zeros or poles, provided that the poles or zeros, respectively, are known.

Conclusions

In finding the zeros of a rational function by the method presented, one finds a sequence of approximate values, each approximate value being obtained from the previous one. The work involved in finding an approximate value is about the same as in substituting a trial value in the original function, because the evaluation of W requires the substitution of the previous approximate value in all but two of the partial fraction terms which constitute the function. Therefore, probably the greatest advantage of the new method is in the possibility of obtaining, with only two sets of computations, a pair of reasonably close approximate values between which the exact zero is known to be located. In many cases the sequences will converge so rapidly that only two terms need be computed, even for good accuracy. If it is necessary to compute more terms of the sequences to improve the accuracy, this method may have less advantage over the trial method, especially if the initial trials should be close to the zeros to be found. However, the new method does not depend on initial chance assumptions, and it is probable that it will at least yield a solution as quickly, on the average, as the trial method, and perhaps much more quickly. There may be some doubt in the reader's mind as to whether these comments apply to the extreme zeros because of the possible lengthened procedure in this case, which may even require a trial substitution. However, the result of the substitution of this trial value is used directly to find a closer approximation, and also, since a lower and upper bound may always be found by explicit means, the range of choice of the trial value is restricted to the interval between these bounds. This possible increased difficulty in finding these zeros is not without its counterpart in the trial method, because the range of choice of trial values extends to infinity, and hence the probability of a good choice is more remote than for the other more restricted zeros.

Of course, the trial method is not the only alternative for finding the zeros of a rational function. They may be obtained by converting the function to the polynomial form and using a method which is applicable to a polynomial, such as Horner's or Graffe's method, or a method suggested by Higgins.[7] However, if the rational function is the impedance or admittance function for the circuits considered here, it will automatically come in the partial-fraction form, and, if there is a large number of terms in the partial-fraction expression, there may be considerable work required to reduce it to the polynomial form. In this case the new method may be preferable, depending on how many of the total number of roots are to be found. This is because the reduction to the polynomial form need be carried out only once, and the work required to find N zeros is therefore less than N times the work required to find the first zero; whereas in the partial-fraction method the work required to find each zero is approximately the same. Hence, the smaller the number of zeros to be found the greater will be the advantage of the partial-fraction method.

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Load Pickup by a Group of Ignitron Rectifiers

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Synopsis: One of the advantages of the application of mercury-arc rectifiers to large electrochemical loads, such as aluminum cell lines, is that, if all the rectifiers are excited simultaneously, they will pick up and share the load together. This eliminates need for large d-c cell-line circuit breakers.

The conventional method of starting simultaneously several ignitron mercury-arc rectifiers, widely used in large electrochemical plants, has been to energize the individual ignitor firing circuits from a master starting switch. Differences in closing time of the control contactors were reflected in proportional irregularity of load pickup between the ignitron rectifiers.

Recent tests, described in this paper, show that the grids usually employed in the ignitrons for anode shielding can be used as an alternative method to energize cell lines. If all the grids are biased negatively, they will prevent current flowing from the rectifiers while the firing circuits are all energized and the switches closed in the power circuits. Then, by operating one switch or a plurality of accurately timed switches, all grids can be made positive at the same instant with the result that all the rectifiers pick up load at the same instant and share it equally.

MANY of the phenomena of the behavior of large rectifier installations, during the instant of applying or dropping electrochemical loads, have been little understood or investigated by engineers. Certain field tests were made in large aluminum reduction plants, the results of which add to the engineering knowledge relating to this subject. Technical advance in the ever-expanding electrochemical field, even though it involves simply a better understanding of the operation of the electrical apparatus in the plant, is important to the engineer. An analysis of the problem and a report of the field tests are contained in this paper.

Among the big five electrochemicals, aluminum, magnesium, chlorine, copper, and zinc, some of the pioneering work and operating experience in connection with aluminum plants stands out because of the tremendous increase in tonnage of aluminum which industry has demanded, particularly for the airplane program. The electrical apparatus required in the reduction of alumina to pure aluminum in the electrolytic cell lines is, however, typical in a great many respects of what is required for the other electrochemicals.

Arrangement of Ignitron Rectifiers

For purposes of this paper, it is necessary to review briefly the heavy electrical equipment involved in a typical large rectifier installation, such as is used for the reduction of aluminum.[1-4] Figure 1 shows a typical one-line power diagram for an aluminum installation. Conversion apparatus for one cell line, for instance, is rated 38,700 kw, 645 volts, 60,000 amperes direct current. The individual electrolytic cells are all connected in series, and each carries the full cell-line current, which under normal conditions may range as high as 50,000 to 55,000 amperes. Since it is impractical to build a power rectifier in a single unit of such large capacity, the conversion apparatus must be broken up into several units. So far, in the United States it has been found impractical to build rectifier transformers in the 600-volt d-c output level larger than 10,000 amperes direct current. Likewise, the largest single rectifier assembly in the 600-volt d-c level is approximately 5,000 to 6,000 amperes direct current. For these reasons, the typical 60,000-ampere rectifier installation is, therefore, arranged as shown in Figure 1 with six separate transformers, each feeding two ignitron-rectifier assemblies.

The fact that single large rectifier installations of this sort must be broken up into several units, however, has its advantages. Since there usually is provided a small amount of extra rectifier and transformer capacity, the scheme is flexible from the maintenance standpoint. For instance, it is usually possible to maintain full current input and, consequently, full production when one unit consisting of a transformer and two rectifier assemblies are out of service for maintenance. For the latter reason, and in order to provide protection from faults and arc-back, power circuit breakers and isolating disconnect switches always are provided.

Earlier large electrochemical cell lines, which were placed in operation before the successful development of mercury-arc rectifiers, were fed from several motor-generators or synchronous converters.[5-7] Since the largest ratings in rotating conversion apparatus compare with the present maximum ratings of single assemblies of power-rectifier equipment, earlier arrangements for connecting the several units to the main d-c bus were very similar to current practice.

Problem of Energizing Cell Line

The method used for energizing large electrolytic cell lines from a battery of several generators or rotary converters has a bearing on the subject of this paper. It was first necessary to bring the generators or converters up to speed. Next, their d-c output voltages were equalized. Since it always has been impossible to build high accuracy in the closing time of d-c air circuit breakers, it was necessary to connect all the separate converting units to the main d-c substation bus before the cell-line load was connected to the bus. This requirement existed because the first machine, whose d-c breaker closed, tended to pick up the complete cell-line load. Since the cell-line load is many times the individual rating of the conversion units, its d-c air circuit breaker would immediately trip on overload. The d-c circuit breakers on the rest of the machines also would clear instantly as they

Table I

Location	Test Numbers	Time After Master Starting Switch Was Closed Before the First Rectifier Started	Maximum Difference in Pickup Time Between First and Last Rectifier Starting
Plant *A*	1	4 cycles	1¾ cycles
Plant *A*	2	4 cycles	2½ cycles
Plant *A*	3	3½ cycles	1½ cycles
Plant *A*	4	3½ cycles	¼ cycle
Plant *A*	5	4½ cycles	1¼ cycles
Plant *B*	1	4½ cycles	1½ cycles
Plant *C*	1	6 cycles	1¾ cycles

In the interval between making plant *A* test 2 and plant *A* test 3, the contactor gap spacings on all 12 ignitor-firing-circuit contactors were readjusted to determine the effects of different contactor closing time on the performance of the various rectifiers. This resulted in changing three factors. First, the time was shortened for picking up the first rectifier. Second, the maximum difference in pickup time between first and last rectifier to start was decreased. Finally, the identity of the first rectifier to pick up load was changed.

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closed in succession. For these reasons the method has never been employed.

As an alternative method, a main d-c circuit breaker, capable of closing in on and carrying the full-load line current, was always employed with rotating converting equipment. This latter breaker was closed only after all the individual units had been connected to the station bus and the full capacity required to carry the load continuously was available.

Obviously, the elimination of this expensive circuit breaker designed to carry and rupture these large and highly inductive loads is desirable.

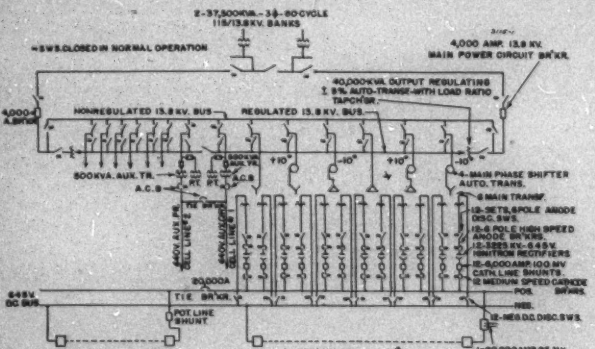

Figure 1. Typical one-line power diagram for cell lines, Aluminum Company of America

One of the advantages of mercury-arc rectifiers over rotating equipment is their ability to pick up electronically such large loads after all the power switching has been completed. There are two general ways of accomplishing this:

1. By controlling the arc in the rectifier with grids.
2. By controlling it with ignitors.

Load Application by Ignitor Control

A widely used method of energizing large cell-line loads supplied by ignitron rectifiers has been to close the a-c and d-c power circuit breakers before exciting the ignitors in the cathode mercury. This means that no current flows from the rectifier, even though all the power circuits are closed, because the ignitors have not caused cathode spots. Magnetic-impulse firing circuits are used widely in such electrochemical service.[8,9] Most magnetic-impulse firing circuits commercially available start generating impulse voltages almost instantly after the contactors in their supply lines are closed and suitable a-c voltage is applied. Advantage has been taken of this performance of the ignitor firing circuits for starting all the rectifiers in a substation at once in order to pick up the large cell-line current.

Where as many as 12 ignitron rectifiers feed a common d-c bus, a master a-c excitation circuit has been used. This has consisted of a 12-pole relay or the equivalent. Each of the 12 poles is connected to the closing coil of a three-pole contactor in the a-c supply circuit to the firing equipment of each of the rectifiers. A single-pole master control switch located in the coil circuit of the 12-pole relays can, therefore, be closed to pick up all of the 12 separate a-c contactors in the supply circuits to the firing equipments.

The procedure, therefore, in picking up ignitron-fed cell-line loads after outages has been rather simple. First, the master excitation switch is opened, which releases all the a-c contactors in the individual firing-circuit supplies. Under this condition, none of the ignitors in any of the rectifiers can create cathode spots to cause current to flow. Next, all of the a-c and d-c power circuit breakers and switches are closed. So far no current flows. The final step then is to close the master a-c excitation circuit energizing all of the separate ignitor firing circuits.

Limitations of This Widely Used Starting Method

The master a-c excitation method of picking up large electrochemical loads fed from ignitron rectifiers has been used for years. As operating experience was gained, it appeared, however, that there were certain limitations. Outages have occurred occasionally because of loss of main a-c supply voltage. Sometimes, when the cell lines were re-energized, one or more of the cathode breakers would trip out from overcurrent. There appeared to be two possible causes for this action:

1. Standard commercial a-c contactors (three-pole) were used in the supply circuits to the individual ignitor firing equipments. While the pickup time of these contactors for most applications is satisfactorily uniform, it was realized that some disparity must exist between the various contactors in closing action. Since cell lines have inductance, it had been anticipated by the application engineers first dealing with the problem that the rate of rise of the cell-line current would be low enough to permit such inequalities in contactor closing time as might appear. Whether this assumption was correct now seemed open to some doubt until tests could be made to substantiate it under field conditions.

2. Resistance characteristics of ignitor firing points are different when the ignitors and liquid mercury in the cathode pools are cold from what they are during operation when the ignitors and mercury are hot. It appeared possible that when the ignitors were cold, such as is the case after a prolonged shutdown, there might be some delay in creating cathode spots in the ignitron rectifiers after the ignitor firing circuits were energized, until the ignitors warmed up and their resistance characteristics improved.

Grid Starting Method

A careful study of the performance of the rectifiers and ignitor firing circuits, was, of course, indicated under the circumstances. It was obvious that satisfactory data could be obtained only under actual field conditions. In anticipation that one or the other, or both, of the foregoing limitations would prove true, an alternative method for starting large ignitron installations feeding electrochemical loads was designed.

Use of Anode Baffle for Grid Control

All large pumped ignitron rectifiers employ a device which in principle is somewhat analogous to the grid in a multianode-type rectifier, but which usually has been called an anode baffle or shield when used in ignitrons. Figure 2 shows the cross section of a single-anode ignitron assembly. Please note the structure surrounding the anode which is called the deionizing anode baffle. This baffle, which is constructed of graphite and insulated from the metal vacuum-tight envelope, is energized through the grid seal. Its function in the ignitron-type rectifier has been to shield the main anode, thereby preventing or minimizing

the occurrence of arc-backs. The fact that it was available, however, suggested that it might be used as another means of controlling the arc.

Factory tests were made to determine whether, with the right negative-bias voltage supplied to these grids, as they should be called when used for such purposes, sufficient control could be obtained to prevent current flowing from the anodes even though the ignitors were energized and firing. These tests indicated that there was enough grid action in the present-type ignitron-insulated anode baffle to prevent current flowing, when the baffles were biased negative with respect to the cathode by 300 volts, under expected conditions of operating temperature and positive main-anode voltages likely to be encountered in this field of application. Satisfactory blocking control could be obtained at this negative-bias level with as many as 500 ohms in series with the biasing circuit. This meant that a practical scheme for grid blocking the main arc in the rectifier could be developed.

Therefore, a cell-line starting circuit based on grid-blocking action in ignitron rectifiers was built. Figure 3 shows the schematic arrangement of a typical grid-bias starting circuit.

Procedure for Energizing Cell Line by Grid Blocking

A procedure for re-energizing a large ignitron rectifier installation after an outage using the Figure 3 circuit is as follows:

1. The 350-volt d-c bias rectifier is energized by closing the fused knife switch and contactor *A* in its supply circuit. In normal operation, the station operator energizes it by closing switch C_1 which is located on his master operating panel.

2. When operator's switch C_1 is closed, all *31S* relays close their contacts, and all the *31SX* relays open their contacts. This action then applies negative 350-volt d-c bias between the cathodes of all the rectifiers and the grids. It is now impossible for any of the rectifiers to carry current so long as this negative bias is maintained.

3. All power circuit breakers and disconnect switches are next closed connecting the rectifiers to both a-c supply voltage and the main d-c station bus.

4. The operator's master a-c excitation switch is then closed, which energizes all the individual firing circuits and causes all the ignitors to start firing. However, no current flows from the rectifiers, because the negative bias is maintaining a blocking action.

5. Finally, the short-circuiting switch *D* is closed, instantly removing the negative bias from all the grids in all the ignitron rectifiers. There remains the 110-volt positive a-c excitation from the baffle transformers, which had been canceled up to this time by the 350-volt negative bias. All 12 ignitron rectifiers, therefore, are permitted to carry current at the same instant.

6. Operator's switches C_1 and C_2 can now be opened. This de-energizes the 350-volt negative-biasing circuit, disconnecting it completely from the main power circuits. It also operates all relays *31S* and *31SX*, transferring the neutrals of the baffle transformers from the master biasing circuit back to the cathode terminals of the rectifiers.

Field Tests

In order to make a thorough study of the problem, it was decided to make extensive tests in the field. Aluminum Company of America operates several reduction plants. Three western plants, all employing rectifiers, were selected. These plants will be designated as plants *A*, *B*, and *C*, for purposes of reference. Initial tests were made on one manufacturer's rectifiers at plant *A*. Confirming tests were made on rectifiers of other manufacture and type at plants *B* and *C* to make them fully comprehensive in nature.

Oscillographic-Test Arrangement

The field tests were conducted by means of oscillographs to obtain the required information. Since there are 12 rectifiers connected to each of the main 60,000-ampere d-c busses for each cell line, it was necessary to use three oscillographs in order to have available enough vibrators to record the behavior of the cathode currents in all 12 rectifiers. By using three oscillographs, 20 vibrators were available.

The three oscillographs were placed on a single operator's table. One vibrator in each oscillograph was connected to a common timing wave, so that the instant of starting the 12 rectifiers would be commonly indicated on the three oscillograms taken for each test. Then four supersensitive vibrators of oscillograph 1 were connected through shunt leads to the ammeter shunts in the cathode lines of rectifiers 1*A*, 1*B*, 2*A*, and 2*B*. Oscillograph 2 had four supersensitive vibrators connected to the four ammeter shunts in cathode lines of 3*A*, 3*B*, 4*A*, and 4*B*, and likewise oscillograph 3 was connected with ammeter shunts in cathode lines of 5*A*, 5*B*, 6*A*, and 6*B*. In each instance, main cell-line current was recorded on one of the films.

Control of the starting operation for all 12 rectifiers was transferred from the operator's main panel in the substation to control switches on the oscillographer's

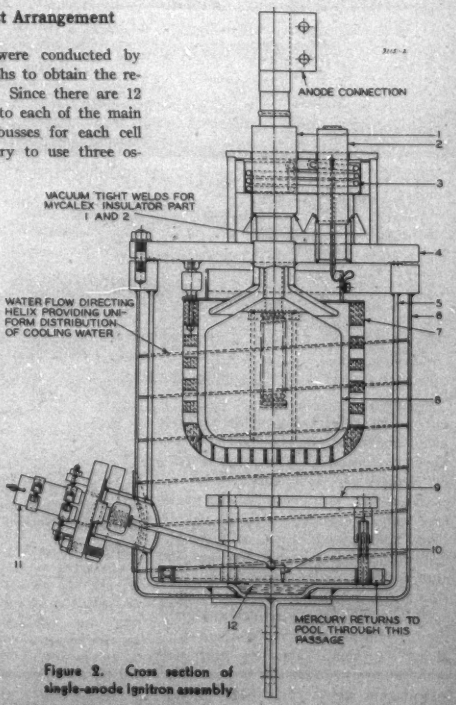
ANODE CONNECTION
VACUUM TIGHT WELDS FOR MYCALEX INSULATOR PART 1 AND 2
WATER FLOW DIRECTING HELIX PROVIDING UNIFORM DISTRIBUTION OF COOLING WATER
MERCURY RETURNS TO POOL THROUGH THIS PASSAGE
1. Mycalex anode insulator
2. Mycalex insulator (lead to insulated baffle)
3. Anode heater
4. Vacuum-chamber cover
5. Vacuum chamber
6. Water jacket
7. Energized (deionizing) anode baffle
8. Graphite anode
9. Mercury splash baffle
10. Ignitor tip
11. Mycalex insulator for ignitor and relieving anode leads
12. Mercury pool (cathode)

Figure 2. Cross section of single-anode ignitron assembly

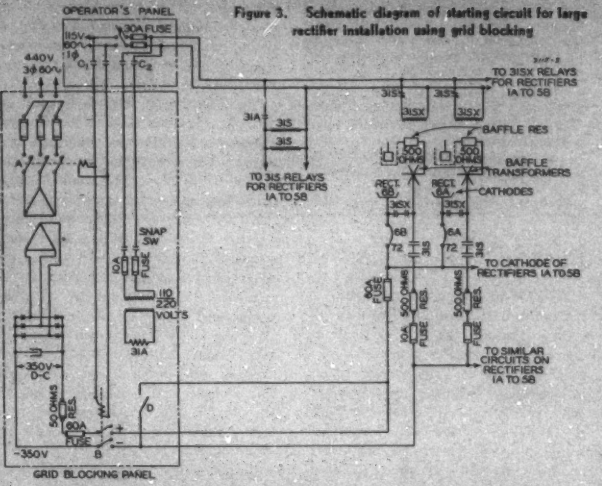

Figure 3. Schematic diagram of starting circuit for large rectifier installation using grid blocking

Figure 4 (below). Typical oscillogram starting cell line by master a-c excitation

On this test the oscillograms for the cathode currents of the other eight rectifiers showed the following results:

1A started 0.72 cycle late
1B started 0.60 cycle late
2B started 0.67 cycle late
3A started 0.64 cycle late
5A started 0.33 cycle late
5B started 0.33 cycle late
6A started 0.72 cycle late
6B started 0 cycle late same instant as 3B. Cathode current for 6B overswung same as 3B. Otherwise behavior of cathode current for these rectifiers was same as shown for 2A, 4A, and 4B

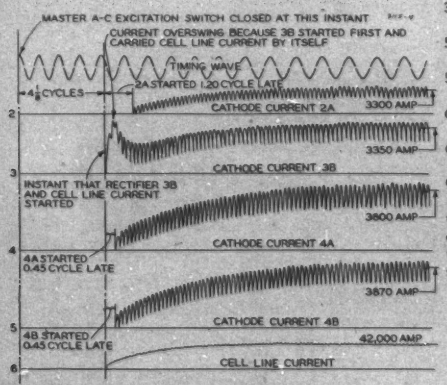
MASTER A-C EXCITATION SWITCH CLOSED AT THIS INSTANT
CURRENT OVERSWING BECAUSE 3B STARTED FIRST AND CARRIED CELL LINE CURRENT BY ITSELF
TIMING WAVE
4½ CYCLES
2A STARTED 1.20 CYCLE LATE
CATHODE CURRENT 2A
3300 AMP
3350 AMP
CATHODE CURRENT 3B
INSTANT THAT RECTIFIER 3B AND CELL LINE CURRENT STARTED
3600 AMP
CATHODE CURRENT 4A
4A STARTED 0.45 CYCLE LATE
3670 AMP
CATHODE CURRENT 4B
4B STARTED 0.45 CYCLE LATE
42,000 AMP
CELL LINE CURRENT

table. All 12 rectifiers would be first taken out of service simultaneously by the station operator. Then, after switching changes were completed quickly, the oscillographer, who controlled the single final starting operation, gave an audible signal, whereupon all three oscillographic instruments were started. The oscillographer, who gave the signal for starting the three oscillographic instruments, operated the master starting circuit for the 12 rectifiers a fraction of a second after giving the signal. This test setup and procedure worked remarkably well. The instruments were synchronized so accurately by their operators that the starting transients occurred on the oscillographic film for all tests less than 30 cycles after the starting signal. At the three plants a total of 13 such tests was made.

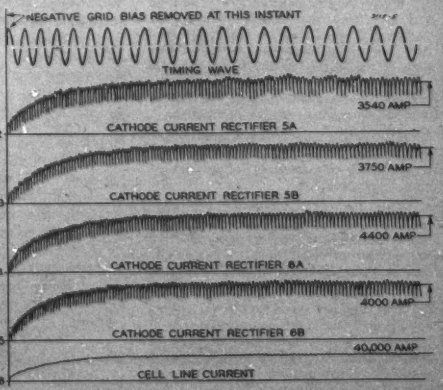

Figure 5. Typical oscillogram starting cell line by grid blocking

Cathode currents for rectifiers 1A, 1B, 2A, 2B, 3A, 3B, 4A, and 4B, started at same instant and had same appearance as cathode currents for 5A, 5B, 6A, and 6B shown on this oscillogram

Results of Starting Tests Using Ignitor Control

Five tests were made at plant *A*, two at plant *B*, and one at plant *C* to record the behavior of the 12 separate rectifiers using the master a-c ignitor-excitation method. Figure 4 is typical of the oscillographic results of these tests. The number of cathode-current records shown in Figure 4 is limited to only 4 of the 12 rectifiers. This was necessary, because an illustration showing the behavior of all 12 rectifiers would be excessively large for publication. However, these four records typify the results.

The results of several of the starting tests using the master a-c ignitor-excitation method to demonstrate the effects or disparity in starting time of the individual rectifier units are given in Table I.

A special test was made at plant *B*, using the master a-c ignitor-excitation method to determine what effect cold ignitors and cathode mercury would have on starting. The volt-amperes output characteristic of the firing circuit used on these rectifiers was lower than on the rectifiers where the other starting tests with master a-c excitation were made. This volt-ampere characteristic was, however, sufficiently high to give satisfactory operation of the ignitors under continuous normal operating conditions after the ignitors and cathode mercury were warm. Results of this special test were that some of the rectifiers delayed as long as 20 to 30 cycles before the ignitors began to fire. Needless to say, with the

various individual rectifiers trying to pick up a cell line at various intervals over such a long period as 20 cycles, each of them tripped out on d-c overcurrent in turn as they started, and the rectifiers failed to energize the cell line.

Results of Starting Tests Using Grid Method

There were five cell-line starting tests made using the Figure 3 grid-blocking methods, two at plant *A* and three at plant *B*. The results of the tests are typically illustrated by Figure 5. For the same reasons as explained for Figure 4, only 4 records of cathode current are shown instead of 12.

During the tests with the grid blocking, the power circuits were all energized and the ignitors caused to fire for a short interval prior to the time when the negative grid bias was removed to pick up the cell-line load. There was no failure of blocking action at any time.

Conclusions

Based on the results of the various tests described, the following conclusions were reached:

1. While the cell-line current requires five to six cycles to reach its steady-state value, its initial rate of rise, while slow referred to the total load, is relatively high referred to the rating of a single rectifier. For this reason, unless all the rectifiers start carrying current at the same instant, when a cell line is energized, the first rectifiers to carry current accumulate load so rapidly that overload can exist in a cycle or less. The three-pole contactors used for the supplies to the individual ignitor-firing circuits were of a standard industrial-control type. A disparity as high as $2^1/_2$ cycles existed in the closing times of these contactors, as proved by the various starting tests. In view of the high rate of rise of cell-line current, if the conventional master a-c ignitor-excitation method of cell-line starting is to be used successfully (excluding effects of cold ignitor points and cold mercury), only contactors having a maximum difference in closing time not greater than one-half cycle should be used.

2. It was proved that the resistance characteristics of cold ignitors may be such that they require substantially higher volt-amperes to cause them to ignite cathode spots, when cold, after a service outage, than under normal operating conditions. Therefore, to insure satisfactory cell-line starting with ignitron rectifiers, the volt-ampere characteristics of the firing circuit must match these extra requirements if the master a-c excitation method is to be employed.

3. The new starting method for large rectifier installations employing the grid-blocking action available in ignitron rectifiers was demonstrated to be practical. The equipment used for making the starting tests by the new grid-blocking method was semipermanently connected in one of the ignitron-rectifier cell-line installations at plant *B*. At least six emergency outages have occurred subsequent to the tests described in the paper. In each instance the new grid-starting method was employed for re-energizing the cell line. All reports show that the scheme was completely successful in all cases. It is, therefore, believed that the grid-blocking method offers a better solution for starting large Ignitron installations of this sort. This conclusion may be reached, because the new method overcomes the difficulty with cold ignitors by permitting the station operators to run them for a sufficient period to warm them up and restore easy ignition characteristics; and it also eliminates the problem of obtaining control contactors having precision closing time, the outcome of which, at best, may be doubtful.

Addendum

During the tests, in addition to solving the problems outlined in the paper, several other interesting and valuable data were obtained. The effect of cell-line inductance in the operation of large electrochemical plants often has been speculated upon by engineers dealing with the problem. Records were obtained of the cell-line-current rate of rise and are shown in Figure 4 and Figure 5.

Cell-line inductance as measured by the starting transients in cell-line current, shown in Figure 4 and Figure 5, has been recognized as a factor affecting the performance of main cell-line breakers in the older installations using rotating apparatus for conversion purposes, and also the cathode breakers, which are used to trip the cell-line currents when shutting down installations employing mercury-arc rectifiers. While it is well known that large air circuit breakers trip with more uniform opening time than they close, nevertheless, the contacts are bound to start parting on some of the cathode breakers earlier than others during planned shutdowns.

Large electrochemical rectifier installations are shut down by operating a master switch which gives simultaneous tripping impulses to all the cathode breakers. When the faster cathode breakers start parting contacts, there is a rapid extinction of current from their associated rectifiers. The remaining rectifiers, whose cathode breakers are slower to open, therefore, accumulate the portion of the load dropped by the earlier rectifiers.

Two important effects, therefore, combine to impose substantially higher interrupting duty on the slower cathode breakers. First, overcurrent exists on one or more of the rectifiers. The magni-

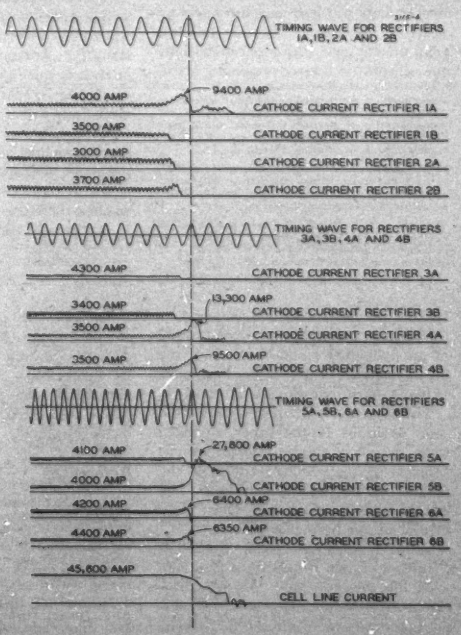

Figure 6. Typical oscillogram showing cathode current in all 12 rectifiers feeding one cell line and total cell-line current when cell line is de-energized by tripping cathode breakers by master tripping switch

The Quadrature Synchronous Reactance of Salient-Pole Synchronous Machines

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Synopsis: Advances in the theory of synchronous machines have created a number of reactance constants, and improvements in theory have led to continual refinements in methods of calculation and test. This paper presents an improvement in the calculation of the quadrature synchronous reactance, compares calculated with test results, and discusses four methods of test, one of which is an improvement in simplicity and ease of accomplishment over methods of test presented previously.

THE wide application of synchronous machines to many methods of power generation and utilization has caused the development and refinement of synchronous-machine theory as a tool to enable the accurate prediction of the behavior of these machines. This theory has created a number of characteristic constants, or coefficients, in terms of which the operation of the synchronous machine is defined. Papers dealing with one or more of these constants have appeared in the pages of the technical press from time to time, each paper broadening the general concepts or presenting methods of calculation or test which more sharply define particular constants.*

Past attention to individual reactance constants has been devoted chiefly to the armature leakage reactance[7] x_l, to the direct-axis quantities[5,6] x_d, x_d', x_d'', and to the negative- and zero-sequence reactances[3,6] x_2 and x_o. Less attention has been paid to the quadrature synchronous reactance[1,2] x_q either in the development of its full theory or in the presentation of test data. The situation is a natural one, as this reactance is not of major importance in either the short-circuit or starting characteristics of machines, and it is these characteristics which have received the most attention. Further, both the classic slip test[4] for x_q and reluctance power test[1] present difficulties in their execution which have discouraged the accumulation of data.

The quadrature synchronous reactance is of prime importance in determining the steady-state torque-angle characteristic which in turn evaluates the spring constant P_r. Accurate knowledge of either or both of these things is necessary when combining synchronous machines with mechanical drives having pulsating shaft torques such as are found in Diesel or gasoline engines and reciprocating compressors. The present tremendous increase in the use of Diesel and gasoline engines therefore makes an analysis of x_q particularly pertinent.

This paper presents refinements in the theory and calculation of x_q and advances two new methods of test for this quantity. It also presents a discussion of the two previously published test methods and compares the results which have been obtained by calculation and by the four test methods.

General Theory, Methods, and Test Results

The quadrature synchronous reactance x_q of salient-pole synchronous machines can be thought of as being made up of two major parts. One of the parts of this quantity is armature leakage reactance x_l the theory of which has been fully presented previously. The second part of this quantity is the reactance of armature reaction. This second quantity x_{aq} exists as a result of the generation of fundamental air-gap flux when armature current flows and the subsequent generation by that flux of a component of armature voltage which opposes an increase in the armature current. The magnitude of the flux and therefore the back voltage depend in part upon the permeance of the air gap opposite the armature magnetomotive-force wave.

In synchronous machines there are two axes of air-gap symmetry, the direct and quadrature axes, and hence two values of gap permeance. Each of these has been determined accurately over the range of variables encountered in modern machine design for unslotted air gaps, but the effect of slots in either or both the armature and field surfaces, while it has been recognized, has not been presented previously in the technical press. Usually the reactance of armature reaction constitutes the major part of x_q, and to predetermine this quantity accurately, its major component must be predetermined

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* See "References."

tude of this current may reach as high as 600 per cent of the full-load current rating of an individual rectifier. Second, the high inductance of the cell-line load tends to maintain current through the breakers.

The opportunity was seized, during the tests described in the paper, to make some records of the behavior of current supplied by the various rectifiers to the d-c bus during cell-line shutdown. The results of these tests are shown in a typical fashion by Figure 6.

Rectifier cathode-current traces in Figures 4, 5, and 6 indicate a high 360-cycle d-c current ripple. Actually, this ripple is substantially lower. It was necessary to use standard d-c shunts instead of oscillograph shunts. With standard shunts the effect of shunt inductance, as well as the effect of fields on shunt leads, is responsible for this apparently large ripple. This must be taken into account in analyzing the oscillograms.

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accurately. In Appendix B a method of calculating the quadrature reactance of armature reaction is presented. This method is based on obtaining the unslotted quadrature-axis air-gap permeance in the conventional manner and then applying to it selected fringing coefficients to account for the slots in the magnetic surfaces. After a value for the reactance of armature reaction has been obtained, the armature leakage reactance is added to it to obtain x_q. The results obtained by calculation are substantiated, as shown in Table I, by several different methods of test.

Unlike the method used for calculating x_p, the test for it must measure the entire quantity, both the armature leakage reactance and the reactance of armature reaction, as it is impossible in test to separate x_q into its analytical components and measure each individually. This restriction places on all test methods the necessity of measuring terminal conditions at an instant when these conditions can be used to evaluate x_q. This instant always occurs just prior to a state of instability, and consequently accurate measurements are not easily made.

In the first method of test, the slip test of Appendix C, an oscillograph is used to record the terminal voltage and armature current as the rotor is forced to slip past the axis of armature magnetomotive force. Unfortunately, the very slip which makes the test possible introduces its own errors. If the slip is large, over $1\frac{1}{2}$ per cent, currents are often induced in the usually present amortisseur windings, and the armature current is influenced by them, so that it may no longer reflect the true rotor permeance. While smaller values of slip can be obtained, they require accurate control of the terminal voltage and ability to adjust it, usually over the range from 20 per cent to 30 per cent of normal voltage. This control and adjustment is seldom available anywhere except on the manufacturer's premises, and it is not always easy to obtain it there for every machine.

The reluctance-torque method, described in Appendix D, is based on the determination of the maximum power the machine will carry when operating as a reluctance motor. The motor, with field open-circuited, can be pulled out of step either by increasing the shaft load with terminal voltage held constant or by reducing the terminal voltage with the shaft load held constant. Since the measurements are always made at the moment of instability, it is important in both of the preceding methods that the shaft load contain no torque pulsations. If the adjustable-shaft-load method is used, it is important that the load be capable of fine adjustment, so that the approach to the point of instability can be made accurately. If the test is taken at no load, the line voltage is reduced until the machine falls out of step because of the friction and windage load. This requires the same type of terminal voltage control necessary in the slip test and hence presents the same difficulties. In addition, it also requires accurate measurement of the friction and windage load.

The negative-excitation test, described in Appendix E, is based on the determination of the amount of field excitation required to overcome the reluctance torque of the machine. The test is taken with the machine operating as a synchronous motor with a free shaft and at rated line voltage, thus eliminating the necessity for a variable voltage supply. It is important in this test that the shaft load be free of torque harmonics and of as small a magnitude as it is possible to obtain. As this small load determines the point of instability, it is important that it be known to calculate x_q.

The fourth and most satisfactory test method, the maximum-lagging-current test, described in Appendix F, uses the same method of test as in the negative-excitation method of Appendix E. In this case it is not necessary to measure shaft power, other than to be sure that it is small, as line voltage and current readings are sufficient. Because the line current is large in size and easy to measure, the test is simpler in its technique than previous methods. Further, a variable line voltage is not required, because, like the negative-excitation test, results can be obtained at rated voltage. The value of x_q is simply the ratio of voltage and maximum stable current.

Thus, in the course of developing various methods of test, the objections have one by one been removed. The necessity of having an oscillograph was first removed, then the requirement of a controlled low-voltage source, and finally the low power readings. The results obtained by the various methods of test are shown in Table I. It was not possible to test each machine included in the table by every test method, and the blanks indicate lack of test data on the particular machine. The agreement is, in general, excellent. No attempt has been made to establish divergences between test and calculation or between test methods. These are apparent from a study of the table itself.

Table I. Quadrature Synchronous Reactance x_q by Calculation and Test

Type of Machine	Kilovolt-amperes	Volts	Frequency (Cycles Per Second)	Rpm	x_q				
					Calculation	Tests			
						Slip	Reluctance Torque	Negative Excitation	Maximum Lagging Current
Motor	1,405	4,160	60	1,800	0.98	1.03	0.98	1.00	0.96
Motor	300	440	60	1,200	1.18		0.97	1.26	1.16
Motor	380	440	60	1,200	1.14	1.09	1.11	1.10	1.14
Industrial-type generator	31.3	208	60	900	0.43	0.42	0.41	0.39	0.43
Motor	900	4,150	60	900	0.98	0.91	1.03	0.98	0.98
Motor	2,700	6,600	60	900	0.98	1.04	1.02	1.00	1.00
Motor	1,160	2,200	60	900	0.74	0.77		0.77	0.72
Motor	1,250	6,600	60	900	0.53	0.54	0.59	0.58	0.57
Motor	1,358	4,100	60	900	0.83	0.83	0.80	0.82	0.82
Motor	2,200	2,200	60	720	0.72	0.71	0.68	0.70	0.70
Motor	1,175	2,200	60	600	0.75	0.77	0.83	0.81	0.82
Motor	5,900	6,600	60	514	1.02	0.96	1.02	0.97	0.98
Motor	2,100	6,600	25	500	0.92	0.92		0.92	0.93
Motor	1,465	2,200	60	450	0.82	0.82		0.84	0.82
Motor	690	4,000	60	400	0.84	0.86	0.85	0.87	0.85
Motor	7,320	6,900	60	400	0.43	0.43			
Industrial-type generator	187	400	50	375	0.53	0.63	0.57	0.63	0.66
Industrial-type generator	500	4,160	60	360	0.60	0.58	0.59	0.57	
Industrial-type generator	625	4,160	60	360	0.65	0.67	0.65	0.67	0.66
Industrial-type generator	375	2,400	60	327	0.75	0.73	0.71		
Motor	205	2,200	60	300	0.99	1.00	0.89	0.95	0.93
Motor	1,380	4,000	60	277	0.77			0.70	0.74
Waterwheel-type generator	6,250	4,150	60	240	0.55	0.57	0.59		
Motor	780	2,300	60	164	1.08	1.09	0.98	1.10	1.08
Waterwheel-type generator	24,000	13,200	60	164	0.58	0.58			0.59

Conclusions

The paper has presented improvements in the method of calculating x_q which enable the accurate prediction of this quantity. It has reviewed two well-known test methods and presented two new ones, one of which, the maximum-lagging-current test, has great advantages in simplicity of technique and ease of accomplishment. These advantages should lead to a wide acceptance of the maximum lagging-current test as a recognized test procedure.

Appendix A. Nomenclature

Electrical quantities, voltage, current, power, reactance, and resistance, are in the unit system and are represented by symbols which have already been generally recognized. Other quantities are, when necessary, defined adjacent to their initial use in the text, and all definitions are consolidated in this appendix.

A = square wave value of armature-reaction ampere turns per pole

A_1 = maximum ordinate of fundamental flux-density wave / maximum ordinate of actual flux-density wave in the air gap of a synchronous machine when excited only from the rotor (saturation is neglected)

A_{g1} = maximum ordinate of fundamental flux-density wave / maximum ordinate of actual flux-density wave that would be produced by the same magnetomotive force acting on a uniform gap equal to g_{min} in the air gap of a synchronous machine when excited by sine wave of armature magnetomotive force in the quadrature axis (saturation is neglected)

C_{fdf} = total fringing coefficient applied to g'_{fdf} to obtain g_{fdf}

C_{fqa} = total fringing coefficient applied to g'_{fqa} to obtain g_{fqa}

e = per unit armature terminal voltage

E = particular value of per unit armature terminal voltage

e_d = per unit direct-axis field excitation, neglecting saturation

E_d = particular value of per unit direct-axis field excitation, neglecting saturation

F = field ampere turns in the air gap required to produce normal voltage in the armature on open circuit

g_{min} = iron-to-iron air gap at the pole center when opposite an armature tooth

g'_{fdf} = apparent air gap seen by the maximum ordinate of the fundamental direct-axis field flux-density wave, neglecting fringing phenomena

g_{fdf} = air gap seen by the maximum ordinate of the fundamental direct-axis field flux-density wave including fringing phenomena

g'_{fqa} = apparent air gap seen by the maximum ordinate of the fundamental quadrature-axis armature flux-density wave, neglecting fringing phenomena

g_{fqa} = air gap seen by the maximum ordinate of the fundamental quadrature-axis armature flux-density wave, including fringing phenomena

I_1 = particular value of per unit line current

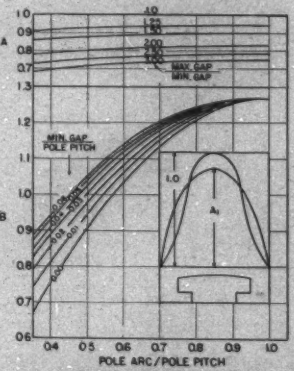

Figure 1. Ratio of the maximum amplitudes of the fundamental component and the actual flux-density waves in the air gap of a synchronous machine excited only from the rotor

Maximum value of actual flux-density wave = unity

Maximum value of fundamental flux-density wave, $A_1 = A \times B$

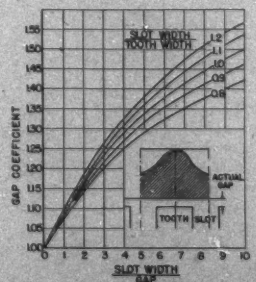

Figure 2. Air-gap fringing coefficient for the flux around a tooth of finite width and a slot of infinite depth as obtained by elliptic function analysis

Use the magnetic gap in place of the actual gap when the two differ

P = per unit value of shaft power (unit power is numerically equal to base kilovolt-amperes)

P_1 = particular value of per unit shaft power

P_r = synchronizing coefficient determined by dividing the shaft power in kilowatts by the corresponding angular displacement in electrical radians of the rotor from its zero shaft power position

Q = per unit value of reactive power (Unit reactive power is base kilovolt-amperes)

Q_1 = particular value of per unit reactive power

r_a = per unit armature resistance

x_l = per unit armature leakage reactance

x_d = per unit direct-axis synchronous reactance

x_q = per unit quadrature-axis synchronous reactance

x_{aq} = per unit quadrature-axis reactance of armature reaction

x = per unit external reactance

δ = load angle in electrical degrees

Γ, T, Ω = quantities defined in equations 20, 22 and 25, respectively

Appendix B. The Calculation of x_q

The quadrature-axis synchronous reactance x_q is defined as the ratio of the fundamental component of reactive armature voltage, due to the fundamental quadrature-axis component of armature current to this component of current under steady-state conditions and at rated frequency. Usually the reactance is taken as the value corresponding to rated armature current.

Alger[7] divided this quantity into two parts, the reactance of armature reaction

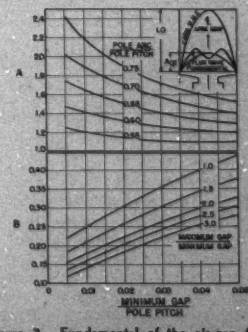

Figure 3. Fundamental of the air-gap flux-density wave when a salient-pole synchronous machine is excited by only a sine-wave armature magnetomotive force whose axis is in quadrature with the pole center

Maximum value of armature magnetomotive force = unity. Fundamental $A_{q1} = A \times B$

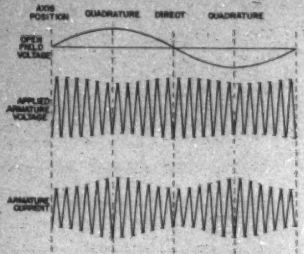

Figure 4. Appearance of oscillogram, slip test for x_q

In practice slip must be the minimum possible and only a small fraction of that illustrated

$$x_q = \frac{\text{per unit applied armature voltage}}{\text{per unit armature current}}$$

where both values are read from the quadrature-axis position

x_{aq}, and the armature leakage reactance x_l, and produced methods for the calculation of x_l. Wieseman,[2] by means of curves derived from flux plots, evaluated coefficients A_1 and A_{g1} which, for smooth air gaps, made possible the determination of the ratio of fundamental air-gap flux due to field magnetomotive force. Linville[4] showed how to use these coefficients to calculate x_{aq}. Both Wieseman's presentation and Linville's employment of it were, as noted, based on smooth gaps. Kilgore[3] pointed out that an "effective" gap, not the actual measured gap at the pole center, must be used when slotted surfaces are considered, but a method of obtaining that effective gap and the employment of the result has not been presented. This, a step needed for the accurate calculation of x_q, is presented here.

The problem can be approached most clearly by first considering the phenomena existing in the direct-axis air gap when the machine is excited only by the field winding. Next, the effect of quadrature excitation from the armature will be introduced, and finally the two effects will be considered jointly to produce an equation for x_{aq}.

Assume, for the moment, that sufficient field excitation is applied to a smooth air gap to produce an actual flux-density wave whose maximum ordinate, at the pole center, is unity. Then from Figure 1, the amplitude of the maximum ordinate of the fundamental of that wave is A_1. The air gap seen by the maximum ordinate of the actual flux-density wave is the iron-to-iron gap at the pole center g_{min}. Since both the actual and fundamental flux-density waves are created by the same magnetomotive force, their different amplitudes indicate that the magnetic gaps seen by the actual and fundamental components are different. Since the ratio of the amplitude of the flux-density waves is A_1, and the gap seen by the maximum ordinate of the actual wave is g_{min}, then the gap seen by the maximum ordinate of the fundamental wave is

$$g'_{fd} = \frac{g_{min}}{A_1} \tag{1}$$

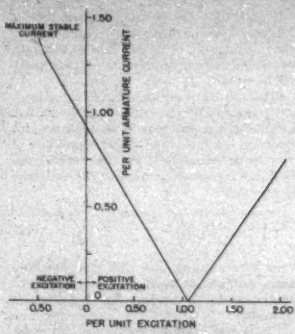

Figure 5. Per unit armature current versus excitation at constant terminal voltage

Carter has derived the relationship between the magnetic gaps of two parallel smooth surfaces and one smooth and one slotted surface. His fringing coefficients, which also can be thought of as "equivalent gap ratios" are well known. Figure 2 shows this coefficient for stator slots over a range of parameters encountered in synchronous machines. Similar characteristics can be obtained for stator air ducts, rotor slots, and other discontinuities in the magnetic surfaces. When these fringing coefficients are applied to the fundamental gap, g'_{fd}, the relationship between the measured iron-to-iron minimum gap and the magnetic minimum gap for the fundamental component of the actual flux wave can be approximated closely.

To use this approximation, the actual iron-to-iron minimum gap, g_{min}, is the starting point. g'_{fd}, the effective smooth gap for the direct-axis fundamental flux-density wave due to rotor excitation, is next found from equation 1. Then using g'_{fd}, the fringing coefficient for the armature slots is found from Figure 2, and similarly, fringing coefficients for other magnetic discontinuities in the air gap are obtained. If the product of the several fringing coefficients for this condition is C_{efd}, then the magnetic gap seen by the fundamental component of the direct-axis field-excited flux-density wave is

$$g_{fd} = C_{efd}\, g'_{fd}$$

$$= C_{efd}\, \frac{g_{min}}{A_1} \tag{2}$$

Figure 3 shows the ratio between the maximum per unit amplitudes of the fundamental component of the flux-density wave and the fundamental magnetomotive-force wave in the quadrature axis when the machine is excited only by a sine wave of armature magnetomotive force in the quadrature axis. If this identical unit magnetomotive-force wave that is applied to the complex smooth gap configuration of Figure 3 were applied to a constant-length smooth gap equal to g_{min}, then the fundamental component of the flux-density wave would be unity. Therefore, the ratio A_{g1} is not only a ratio between a magnetomotive-force wave and a flux-density wave,

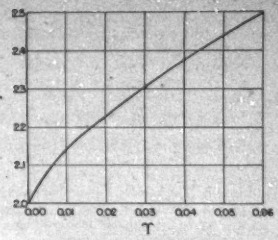

Figure 6. Plot of equation 22

but may also be thought of as the ratio between the fundamental component of quadrature-axis armature flux and unit fundamental armature flux, both of which are created by unit fundamental armature magnetomotive force. Hence, like A_1, it also is an inverse ratio of magnetic gap and the gap seen by the maximum ordinate of the fundamental quadrature-axis armature flux is

$$g'_{fqa} = \frac{g_{min}}{A_{g1}} \tag{3}$$

If similar approximations are applied to g'_{fqa} as were applied to g'_{fd} to get the appropriate fringing coefficients, the magnetic gap seen by the fundamental component of quadrature axis armature flux is

$$g_{fqa} = C_{efqa}\, g'_{fqa}$$

$$= C_{efqa}\, \frac{g_{min}}{A_{g1}} \tag{4}$$

Under the assumption of smooth air-gap surfaces and with the application of identical fringing coefficients to all methods of excitation, the relationships determining x_{aq} have been shown to be[4]

$$x_{aq} = \frac{4}{\pi}\, \frac{A}{F}\, \frac{A_{g1}}{A_1} \tag{5}$$

When the fringing coefficients are recognized to be different and dependent upon the method of excitation, as set forth here, this equation becomes

$$x_{aq} = \frac{4}{\pi}\, \frac{A}{F}\, \frac{A_{g1}}{A_1}\, \frac{C_{efd}}{C_{efqa}} \tag{6}$$

Also there is the relationship

$$x_q = x_l + x_{aq} \tag{7}$$

Therefore

$$x_q = x_l + \frac{4}{\pi}\, \frac{A}{F}\, \frac{A_{g1}}{A_1}\, \frac{C_{efd}}{C_{efqa}} \tag{8}$$

Appendix C. The Slip Test For x_q

The slip test for x_q has already been presented adequately in the technical press,[9] and so only a brief description is necessary. The machine to be tested is either coupled to a second machine or run with a free shaft and positive-sequence voltage applied to the terminals. The field winding is open-circuited. The terminal voltage or shaft torque is then adjusted so that the reluctance

torque of the machine is overcome, causing the field to slip past the armature magnetomotive-force wave at a low value of slip. An oscillographic record of the armature current, terminal voltage, and induced field voltage, is then taken. Figure 4 illustrates the appearance of such an oscillogram.

The quadrature synchronous reactance equals the minimum ratio of the per unit armature voltage and current read from the oscillogram. The correct values of armature voltage and current are obtained at those instances when the induced field voltage is at a positive or negative maximum.

The slip method of measurement, using an oscillograph, has the advantage of measuring most clearly those quantities on which the definition of x_q is based and of providing a permanent record of the quantities read. It also has disadvantages. Since the terminal voltage applied must usually be approximately 20 per cent to 30 per cent of the rated voltage and must be adjusted accurately, a controllable low-voltage power supply is required. It is important that the slip be very small; otherwise in machines having amortisseur windings, currents will be induced in these windings, and the reactances read from the oscillogram will be low. Even under the most strictly controlled conditions the instantaneous slip of the rotor is usually a minimum when the stator magnetomotive force is passing through the quadrature axis, and hence a difference between the accuracies of x_d and x_q, as read by the oscillogram, is inherent in the method.

For these reasons the slip method is generally limited to testing in the manufacturer's plant and is not broadly suitable for field work.

Appendix D. Reluctance Torque Test for x_q

Kingsley[1] first suggested the reluctance-torque test for x_q. Neglecting losses, the power-angle equation of an ideal synchronous machine connected to an infinite bus is given by[10]

$$P=\frac{ee_d}{x_d}\sin\delta+\frac{e^2(x_d-x_q)}{2x_dx_q}\sin 2\delta \tag{9}$$

If the machine is operated as a reluctance motor, $e_d=0$, and maximum synchronous power will occur when $\sin 2\delta=1.0$ (that is, $\delta=45$ degrees). Any change tending to increase δ will cause loss of synchronism.

By lowering the terminal voltage or increasing the shaft load, the machine may be made to pull out of synchronism. Knowing x_d from other tests, and determining E and P_1 at the point at which loss of synchronism occurs, x_q can be found from the relation

$$x_q=\frac{E^2x_d}{E^2+2P_1x_d} \tag{10}$$

It can be shown that the effect of armature resistance is approximately taken into account by the equation

$$x_q=\frac{E^2(x_q+2r_a)}{E^2+2P_1x_d} \tag{11}$$

If P_1 is only the friction and windage of the machine, the drop-out voltage will be low (15 per cent to 25 per cent of normal), saturation will not be present, and core losses will be small.

Errors in the measurement of the power, and particularly the pull-out voltage, are possible as the machine is unstable as this condition is approached. The magnitude of error in determining x_q can be found from the following equation, which is derived from equation 10:

$$\frac{dx_q}{x_q}=\left(1-\frac{x_q}{x_d}\right)\left(2\frac{de}{e}-\frac{dP}{P}\right) \tag{12}$$

Reactance external to the test machine causes pull-out at some angle less than 45 degrees, and the calculated value of x_q is too high.

If x is the external reactance, the load angle at pull-out is found to be

$$\delta=\text{arc tan}\frac{x_q}{x_d}\frac{(x_d+x)}{(x_q+x)} \tag{13}$$

The value of x_q is then given by

$$x_q=\frac{E^2(x_d\sin 2\delta+2r_a)}{E^2\sin 2\delta+2P_1x_d} \tag{14}$$

If the effects of armature resistance and external reactance are neglected, the error is given, very closely, by the relation

$$\frac{\Delta x_q}{x_q}\simeq\left(1-\frac{x_q}{x_d}\right)(1-\sin 2\delta) \tag{15}$$

The reluctance-torque test for x_q has one advantage over the slip test, namely, that satisfactory readings are possible without the use of an oscillograph. It has many of the disadvantages of the slip test. Again a controllable low-voltage source is usually required, and tests are generally possible only on the manufacturer's premises. In addition, shaft power must be known accurately.

Appendix E. Negative-Excitation Test for x_q

The negative-excitation test for x_q derives its name from the reversed polarity which is imposed on the field winding when the instruments are read and the necessity of recording this value. The machine to be tested is run as a synchronous motor, with a free shaft and with constant applied rated terminal voltage. The field current is initially adjusted to its value at the low point in the V-curve characteristic. It is then decreased to zero, causing an increase in line current, and, after reaching zero field current, the polarity of the applied excitation is reversed and field current increased in the negative direction, causing a continuing increase in the armature current. See Figure 5. By applying small increments in field current as the maximum stable negative field current is approached, the highest per unit value E_d of field current that can be obtained is found. Per unit shaft power, P_1, at this point is also determined. If the per unit direct-axis synchronous reactance x_d is known from other tests, x_q can then be found from the two readings taken.

Neglecting losses and applying negative excitation, the power-angle equation 9 becomes

$$P=\frac{e(-e_d)}{x_d}\sin\delta+\frac{e^2(x_d-x_q)}{2x_dx_q}\sin 2\delta \tag{16}$$

When the machine is operating at its maximum stable point, there is

$$\frac{dP}{d\delta}=0 \tag{17}$$

and

$$\frac{ee_d}{x_d}\cos\delta=\frac{e^2(x_d-x_q)}{x_dx_q}\cos 2\delta \tag{18}$$

from which

$$\delta=\text{arc cos}\frac{1.0+\sqrt{1+2\Gamma^2}}{2\Gamma} \tag{19}$$

where

$$\Gamma=\frac{2e}{e_d}\left(\frac{x_q}{x_d}-1.0\right) \tag{20}$$

Combining and simplifying equations 16, 19 and 20 there results

$$P=\frac{ee_d}{x_d}\Upsilon \tag{21}$$

where

$$\Upsilon=\sqrt{\frac{(\sqrt{1.0+2\Gamma^2}-3.0)^2}{32(\sqrt{1.0+2\Gamma^2}-1.0)}} \tag{22}$$

Equation 22 is plotted in Figure 6.

If test values of $P(P=P_1)$, $e_d(e_d=E_d)$, $e(e=E)$, and x_d are substituted in equation 21, there is

$$\Upsilon=\frac{P_1x_d}{EE_d}$$

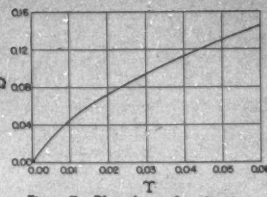

Figure 7. Plot of error function Ω

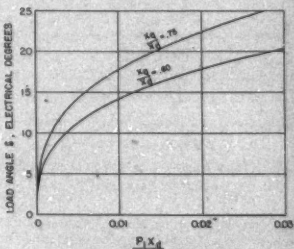

Figure 8. Plot of equation 31

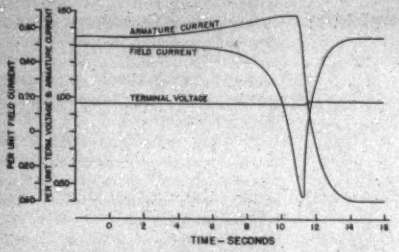

Figure 9. Terminal characteristics during a negative-excitation slip cycle

and the quantity T can be evaluated by test. Figure 6 can then be used to evaluate Γ, and from equation 20

$$x_q = \frac{x_d}{\frac{\Gamma E_d}{2E} + 1.0} \tag{23}$$

Test errors may occur in the determination of E_d and P_1. It can be shown that, if such errors do occur, the effect on x_q can be evaluated from the relationship

$$\frac{dx_q}{x_q} = -\left(1.0 - \frac{x_q}{x_d}\right)\left(\Omega \frac{dP_1}{P_1} + (1.0 - \Omega)\frac{dE_d}{E_d}\right) \tag{24}$$

where

$$\Omega = \frac{\sqrt{1.0 + 2\Gamma^2} - 3.0}{\sqrt{1.0 + 2\Gamma^2} + 1.0} \tag{25}$$

The error function Ω is plotted against T in Figure 7 for the range of T usually encountered. A study of this reveals that the value of x_q so determined is more affected by a test error in E_d than by a corresponding one in P_1.

The negative-excitation test for x_q, has an important advantage over both the slip and reluctance-torque methods of test in that a controllable low-line-voltage source is not required. Tests can be made on the user's premises where rated line voltage is frequently the only source of power, but, as in the reluctance-torque test, shaft power must be known, and this introduces the problem of measuring it.

Appendix F. Maximum-Lagging-Current Test for x_q

The maximum-lagging-current test for x_q is made in exactly the same manner as the negative-excitation test discussed in Appendix E. With the machine operating with a free shaft and with constant terminal voltage applied, the maximum stable per unit line current I_1, corresponding to the maximum stable negative excitation E_d, is found. x_q can then be found from these line-voltage and line-current values.

Neglecting losses and applying negative excitation as in Appendix E, the magnitude of negative excitation at the maximum stable operating point is, by solving equation 18, found to be

$$e_d = \frac{e(x_d - x_q)}{x_q} \frac{\cos 2\delta}{\cos \delta} \tag{26}$$

The general reactive-power-angle equation of a synchronous machine connected to an infinite bus is

$$Q = \frac{e e_d}{x_d} \cos \delta - \frac{e^2}{x_d} \cos^2 \delta - \frac{e^2}{x_q} \sin^2 \delta \tag{27}$$

When negative excitation, as given in equation 26, is applied to equation 27, the maximum stable reactive power is

$$Q_1 = -\frac{e^2}{x_q}\left[1 - \left(1 - \frac{x_q}{x_d}\right)\sin^2 \delta\right] \tag{28}$$

In an ideal machine operating at no load with no losses, the load angle δ and the active power P are both zero when maximum reactive power is reached.

For these conditions

$$Q_1 = EI_1 = -\frac{E^2}{x_q} \tag{29}$$

and in magnitude

$$x_q = \frac{E}{I_1} \tag{30}$$

In an actual machine, power must be developed to overcome friction and windage, and the load angle at the maximum stable point cannot be zero. However, neglecting armature losses, it can be shown as follows that for the usual range of machine constants and friction and windage losses, these effects produce negligible errors in equation 30.

If equation 26 is substituted in equation 9, the power P_1 with negative excitation and at the maximum stable point is

$$P_1 = \frac{E^2(x_d - x_q)}{x_d x_q} \sin^2 \delta \tan \delta \tag{31}$$

Figure 8 is a plot of equation 31 showing the relationship between δ and $P_1 x_d / E^2$ over a range of machine constants. It can be seen from Figure 8 that at normal voltage and with usual values of x_d and P_1, δ may be as large as 20 degrees but probably will not exceed 15 degrees. If $\delta = 20$ degrees, and $x_q/x_d = 0.6$, equation 28 gives a value for Q_1 which is 95.7 per cent of the maximum possible value given by equation 29. Hence, x_q, as determined by equation 30, would be approximately five per cent high. The inclusion of armature losses will decrease this figure slightly. It is felt that this figure of five per cent is a reasonable maximum variation between x_q determined by this method and the correct value and that in most cases the error will be less than five per cent. Table I justifies this conclusion.

The terminal characteristics during a typical negative-excitation slip cycle have been recorded on oscillograms. Figure 9 shows the envelopes of the terminal voltage and armature current and a trace of the field current during one of these cycles. Previous to time $t = 0$, the machine was operating at the maximum-stable-armature-current point of Figure 5. At $t = 0$ the field voltage was slightly increased, and the machine became unstable and started to slip. As the slip increased, the armature current increased, reaching a maximum unstable value at $t = 11$ seconds. As the unstable region was passed, the armature current fell until at $t = 16$ seconds it was operating stably on the positive excitation side of the V curve of Figure 5. This phenomenon of rise and fall in current, when passing through the slip cycle, is readily apparent on test meters. The maximum stable current, not the maximum current during slipping, is used to determine x_q.

The maximum-lagging-current test for x_q has a great advantage over all other test methods in that the instruments required are perfectly standard and widely available. The test is made at rated voltage, and shaft power is not required to calculate the results. It is by far the simplest of the methods presented.

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Practical Calculation of Electrical Transients on Power Systems

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Synopsis: Solution of many power-circuit problems depends upon the magnitude, duration, and frequency of occurrence of transient voltages and currents produced by circuit changes. Circuit-opening or recovery-voltage transients are fundamental in the operation of interrupting devices and may be important from the standpoint of the dielectric strength of circuit elements. Circuit-closing transients may be important from the standpoint of inrush currents and occasionally from the standpoint of overvoltages. Both types of transients may be increased greatly if restriking and repetitive interruptions take place.

Transient voltages and currents resulting from circuit changes can be calculated by the classical method with the aid of differential equations or by the Heaviside method, particularly with the aid of the expansion theorem. Transients on complicated power systems are most conveniently determined by the miniature-system method introduced by Evans and Monteith and described in their 1937 AIEE paper.[1] Analytical methods are useful for simple problems and are essential for those beyond the range of the a-c network calculator or when it is not available. Analytical methods are also necessary for determining the proper form of the equivalent networks for the representation of power systems on the a-c network calculator. This circumstance provided the occasion for the particular investigation for which the present paper is a partial report.

This paper is devoted to the practical calculation of power-system transients and presents concepts, methods, and approximations selected with that objective in view. The paper describes a method of calculation particularly adapted for engineering work.

The scope of the present paper is limited to networks consisting of constant inductance and constant capacitance elements without loss. Consideration of such networks facilitates the presentation of the subject, and gives an adequate view of the phenomena involved. The presentation is from the standpoint of the electrical engineer who is accustomed to making steady-state calculations but who has not given the special study to the transient problem required by the mathematical approach generally used.

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THE classical method of determining the transients produced by the application of voltage or current to a network is carried out by setting up a set of linear differential equations. The general solution of the set of equations for the case of a suddenly applied voltage may be written as follows:

$$i(t) = A_s(t) + A_1 \sin \omega_1 t + A_2 \sin \omega_2 t \ldots A_n \sin \omega_n t \quad (1)$$

In this equation, ω_1, ω_2 ... ω_n are the modes of oscillation of the network ($2\pi \times$ natural frequencies); A_1, A_2 ... A_n are the constants that define the amplitudes of the corresponding modes; and $A_s(t)$ is the term that defines the steady-state current and the nonoscillatory components of the transient current. The integration constants A_1 ... A_n can be determined from the boundary conditions in the usual manner. A corresponding equation may be written for the voltages produced by the application of current to a network.

The general solution of the transient problems in networks is readily accomplished in a formal manner, but considerable work remains before the numerical answers are obtained. Determination of the modes of oscillation, although required by all methods (at least for principal terms), involves considerable labor when the equations are of a high degree. Determination of the integration constants, while straightforward from a mathematical point of view, frequently offers considerable difficulty to engineers not accustomed to transient calculations. Because of the limitations of the classical method, the analytical work presented in this paper has been based on the Heaviside expansion theorem. Before taking up the method of analysis described in this paper, it is desirable to discuss in some detail the general properties of no-loss networks.

Properties of Networks

The reactance and susceptance characteristics of networks are fundamental to the method of analysis described in this paper and so will be discussed first. The reactance properties are used when the method is employed in solving circuit-closing problems, whereas the susceptance properties are used in circuit-opening problems. Accordingly, the discussion of networks is arranged in two parts, one for circuit-closing and the other for circuit-opening problems.

All no-loss two-terminal networks consisting of fixed circuit elements are of four types, depending only on the reactances at zero and at infinite frequencies. The principal characteristics of these four types of networks are given in Table I. The network can be typed readily by considering the character of the paths between the driving-point terminals as shown in the table. For example, type I networks have no paths between terminals containing inductance or capacitance alone, that is, all paths contain both elements. Representative networks of the four types are illustrated in the table. Angular velocity-reactance curves corresponding to the representative networks are also given in Table I. These curves are obtained by calculating the steady-state reactance as a function of angular velocity in the usual manner.

The network-reactance curves are discontinuous functions that start from negative infinity and increase to zero or to positive infinity or that start at zero and increase to positive infinity. In other words, all reactance curves have positive slopes[2] throughout their continuous portions. The infinite-reactance points or points of discontinuity are termed "poles," and the zero-reactance points are termed "zeros." These definitions are in accordance with accepted terminology and are used in the subsequent discussion of network characteristics. The "zeros" and "poles" at zero and at infinite frequencies are called "external zeros" and "external poles" and the remaining ones are called "internal zeros" and "internal poles." As can be seen readily from the reactance curves of Table I, the external zeros and poles also define the network type; for example, the type I network has poles at zero and at infinite frequencies. The number of internal zeros that a network has is equal to the number of modes of oscillation; this number is also equal to the maximum number of meshes containing both independent inductive and capacitive elements.

Basic equivalent networks in a form convenient for circuit-closing transients are also included in Table I for each network type. In the basic networks there is one branch containing both L and C for each internal zero; in addition, there are other branches containing only L or only C as required to correspond to the

external zeros. A branch containing L alone is required when the network has a zero at zero frequency and a branch containing C alone is required when the network has a zero at infinite frequency. Thus a network of type IV, having zeros at zero and at infinite frequencies, requires one branch with L alone and one branch with C alone.

All no-loss two-terminal networks can also be classified according to the network susceptance at zero and infinite frequencies, as shown in Table II. The representative networks in Table II are identical to the corresponding types in Table I. The angular velocity-susceptance curves are included in the table for each network type. Basic equivalent networks of the form convenient for circuit-opening transients are also included in Table II.

Method of Zeros and Slopes

As the method of analysis to be described depends upon the zeros and slopes of the reactance (or susceptance) curves for the networks, it is referred to as the method of "zeros and slopes." The method is described under two headings:

(a). Unit voltage applied.

(b). Unit current applied.

The method will be extended for the application of a-c voltages and currents in a later section.

(a). Unit Voltage Applied

The response of a network to a suddenly applied unit voltage is given by the Heaviside expansion theorem as follows:

$$i(t) = i_s(t) + \sum_{k=1}^{k=m} \frac{e^{p_k t}}{p_k Z'(p_k)} \qquad (2)$$

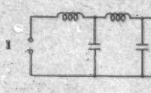
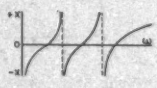
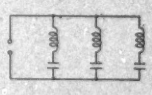
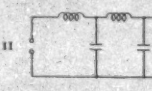
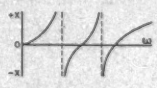
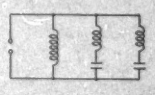
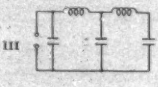
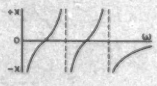
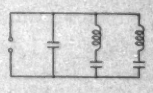
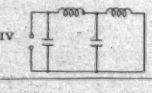
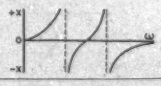
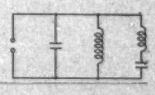
In this form of the expansion theorem, the function $i_s(t)$ defines the steady-state network solution and that part of the transient solution determined by the external zeros. The term $Z'(p)$ is the first derivative of $Z(p)$ with respect to p, where $Z(p)$ is the impedance function of the network as viewed from the driving point. The summation indicates that there are as many terms in the transient solution (neglecting the $i_s(t)$ term) as there are roots of the equation $Z(p)=0$. The quantity p_k is a general expression for the roots of $Z(p)=0$.

It is shown in the appendix that when restricted to no-loss networks, equation 2 can be written in the following approximate form:

$$i(t) = i_s(t) + A_1 \sin \omega_1 t + A_2 \sin \omega_2 t + \ldots + A_n \sin \omega_n t \qquad (3)$$

Table I. Classification of Networks for Circuit-Closing Transients

Type	X at $\omega=\infty$	X at $\omega=0$	Paths: C Alone	Paths: L Alone
I	∞	∞	None	None
II	∞	0	None	At least one
III	0	∞	At least one	None
IV	0	0	At least one	At least one

Type	Typical Networks	Typical Reactance Curves	Basic Equivalent Networks
I			
II			
III			
IV			

where

$$A_1 = \frac{2}{\omega_1 \dfrac{\Delta X}{\Delta \omega_1}}; \quad A_2 = \frac{2}{\omega_2 \dfrac{\Delta X}{\Delta \omega_2}}; \quad \ldots A_n = \frac{2}{\omega_n \dfrac{\Delta X}{\Delta \omega_n}}$$

The $i_s(t)$ term defines the steady-state current and the components of the transient current corresponding to the external zeros. This term is given in Table III for each type of network. The term t/L_e defines a current starting at zero and increasing directly with time to an infinite value at $t=\infty$. The term $\left[\dfrac{t}{C_e}\right]_{t=0}$ defines a current having an infinite magnitude at $t=0$ and equal to zero thereafter, such as instantly to bring the charge on the capacitance to the applied voltage. The quantity L_e is defined as the equivalent inductance between driving-point terminals with all capacitances open-circuited, and C_e is the equivalent capacitance with all inductances open-circuited.

In equation 3, $\omega_1, \omega_2, \ldots \omega_n$ are the values of angular velocity corresponding to zero reactance between the driving-point terminals, and $\dfrac{\Delta X}{\Delta \omega_1}, \dfrac{\Delta X}{\Delta \omega_2}, \ldots \dfrac{\Delta X}{\Delta \omega_n}$ are the slopes of the angular velocity-reactance curve at the corresponding values of angular velocity. This relation shows that the response of a no-loss network can be determined from the steady-state reactance characteristics of the network. An approximate solution can, therefore, be obtained by calculating the angular velocity-reactance curve and then determining the slopes of the curve at or near the zeros. This procedure is illustrated in Figure 1 for a relatively simple circuit. It should be noted that it is not necessary to obtain the complete curve but only those parts in the vicinity of the zeros. The number of points that must be calculated will depend upon the accuracy desired and on the ability of the operator to estimate the zeros. The accuracy of the solution will depend entirely on the accuracy with which the zeros and slopes are evaluated.

(b). Unit Current Applied

The problem of calculating the transient voltage following the opening of a circuit can be analyzed in terms of the original current and a suddenly applied equal and opposite current.* The superposition of these two currents reduces the total current to zero, which is equivalent to opening the circuit. Thus, the first step is to calculate the network response to unit current.

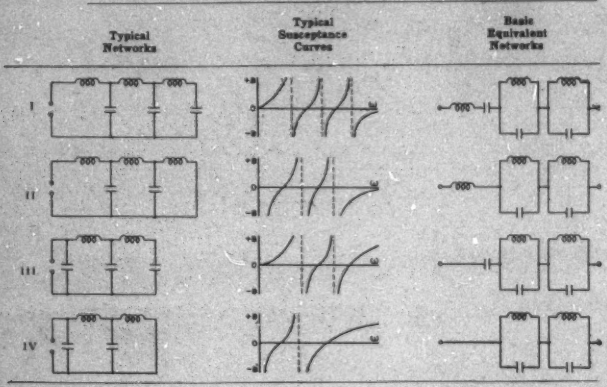
The response of a network to a suddenly applied unit current can also be written in a form similar to equation 3.

$$e(t) = e_s(t) + A_a \sin \omega_a t + A_b \sin \omega_b t + \ldots + A_m \sin \omega_m t \qquad (4)$$

* Page 306 of reference 1.

Table II. Classification of Networks for Circuit-Opening Transients

Type	B at $\omega=\infty$	B at $\omega=0$	Paths: C Alone	Paths: L Alone
I	0	0	None	None
II	0	∞	None	At least one
III	∞	0	At least one	None
IV	∞	∞	At least one	At least one



where

$$A_a=\frac{2}{\omega_a}\frac{\Delta B}{\Delta\omega_a};\ A_b=\frac{2}{\omega_b}\frac{\Delta B}{\Delta\omega_b};\ \ldots A_m=\frac{2}{\omega_m}\frac{\Delta B}{\Delta\omega_m}$$

The $e_s(t)$ term defines the steady-state voltage and the components of the transient voltage corresponding to the external zeros. This term is given in Table III for each type of network. The term t/C_s defines a voltage starting at zero and increasing directly with time to an infinite value at $t=\infty$. The term $\left[\frac{L_o}{l}\right]_{t=0}$ defines a voltage having an infinite magnitude at $t=0$ and equal to zero thereafter. The quantity C_s is the equivalent capacitance between driving-point terminals with all inductances short-circuited, and L_o is the equivalent inductance with all capacitances short-circuited.

Table III

Network Type	$i_o(t)$	$e_s(t)$
I	0	$\left[\frac{L_o}{l}\right]_{t=0}+\frac{t}{C_s}$
II	$\frac{t}{L_o}$	$\left[\frac{L_o}{l}\right]_{t=0}$
III	$\left[\frac{C_o}{l}\right]_{t=0}$	$\frac{t}{C_s}$
IV	$\frac{t}{L_o}+\left[\frac{C_o}{l}\right]_{t=0}$	0

L_o = Equivalent L determined with all C's short-circuited
L_s = Equivalent L determined with all C's open-circuited
C_o = Equivalent C determined with all L's open-circuited
C_s = Equivalent C determined with all L's short-circuited

In equation (4), $\omega_a, \omega_b, \ldots \omega_m$ are the values of angular velocity resulting in zero susceptance between driving-point terminals, and $\frac{\Delta B}{\Delta\omega_a}, \frac{\Delta B}{\Delta\omega_b}, \ldots \frac{\Delta B}{\Delta\omega_m}$ are the slopes of the angular velocity-susceptance curve at the corresponding points. The response of a no-loss network to unit current can, therefore, be obtained in a manner similar to that illustrated for the response to unit voltage. However, in this case the steady-state susceptance characteristics of the network are used instead of the reactance characteristics.

Equivalent Networks

Every network can be reduced to an equivalent network[3,5] of either the shunt or series forms, illustrated in Figure 2. The basic equivalent network of the shunt form is advantageous for circuit-closing transients because of the lack of coupling between branches for this type of circuit change. Similarly, the basic equivalent network of the series form is advantageous for circuit-opening transients. These equivalent networks are helpful in visualizing the properties of networks and in interpreting the equations of transient response. Furthermore, the replacement of a given complicated network by the simplest equivalent network of a given form is advantageous under many circumstances for calculation by analytical or a-c network calculator methods.[4]

(a). Circuit-Closing Transients

The basic equivalent network in the shunt form of Table I can be derived from the network response to unit voltage as given by equation 3. For convenience this equation has been rewritten with the $i_o(t)$ term expanded as given in Table III:

$$i(t)=\frac{t}{L_o}+\left[\frac{C_o}{l}\right]_{t=0}+A_1\sin\omega_1 t+ A_2\sin\omega_2 t\ldots A_n\sin\omega_n t \quad (5a)$$

$$=\frac{t}{L_o}+\left[\frac{C_o}{l}\right]_{t=0}+\frac{2}{\omega_1}\frac{\Delta X}{\Delta\omega_1}\sin\omega_1 t+ \frac{2}{\omega_2}\frac{\Delta X}{\Delta\omega_2}\sin\omega_2 t\ldots\frac{2}{\omega_n}\frac{\Delta X}{\Delta\omega_n}\sin\omega_n t \quad (5b)$$

The basic equivalent network of the shunt form is illustrated in Figure 2a. Each branch of this equivalent network corresponds to one term of the network solution given by equation 5. The L_o and C_o branches correspond, respectively, to an equivalent inductance or an equivalent capacitance in parallel with the driving-point terminals, as defined in Table III. As the response of a simple series LC circuit to unit voltage is $\sqrt{\frac{C}{L}}\sin\omega t$, where $\omega=\frac{1}{\sqrt{LC}}$, equation 5 can be written in the following form:

$$i(t)=\frac{t}{L_o}+\left[\frac{C_o}{l}\right]_{t=0}+\sqrt{\frac{C_1}{L_1}}\sin\omega_1 t+ \sqrt{\frac{C_2}{L_2}}\sin\omega_2 t\ldots\sqrt{\frac{C_n}{L_n}}\sin\omega_n t \quad (6)$$

where

$$\omega_1=\frac{1}{\sqrt{L_1C_1}};\ \omega_2=\frac{1}{\sqrt{L_2C_2}};\ \ldots\omega_n=\frac{1}{\sqrt{L_nC_n}}$$

By equating the coefficients of equations 5a and 6, the remaining circuit elements of the equivalent network can be determined as follows:

$$\left.\begin{aligned} &A_1=\sqrt{\frac{C_1}{L_1}};\ A_2=\sqrt{\frac{C_2}{L_2}};\ \ldots\ A_n=\sqrt{\frac{C_n}{L_n}}\\ &\omega_1=\frac{1}{\sqrt{L_1C_1}};\ \omega_2=\frac{1}{\sqrt{L_2C_2}};\ \ldots\omega_n=\frac{1}{\sqrt{L_nC_n}}\\ &C_1=\frac{A_1}{\omega_1};\ C_2=\frac{A_2}{\omega_2};\ \ldots\ C_n=\frac{A_n}{\omega_n}\\ &L_1=\frac{1}{\omega_1A_1};\ L_2=\frac{1}{\omega_2A_2};\ \ldots\ L_n=\frac{1}{\omega_nA_n} \end{aligned}\right\} \quad (7)$$

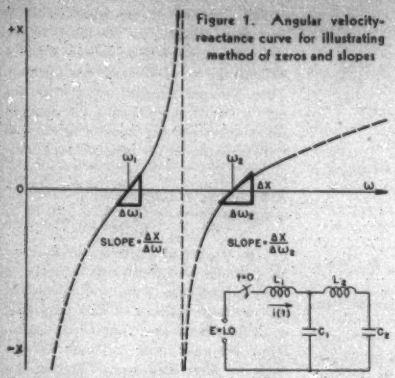
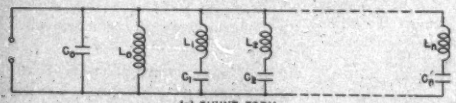
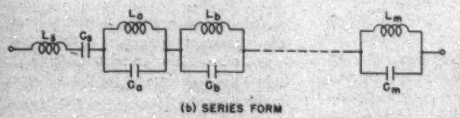


Figure 1. Angular velocity-reactance curve for illustrating method of zeros and slopes



(a) SHUNT FORM



(b) SERIES FORM

Figure 2 (left). Basic equivalent networks in the shunt and series forms

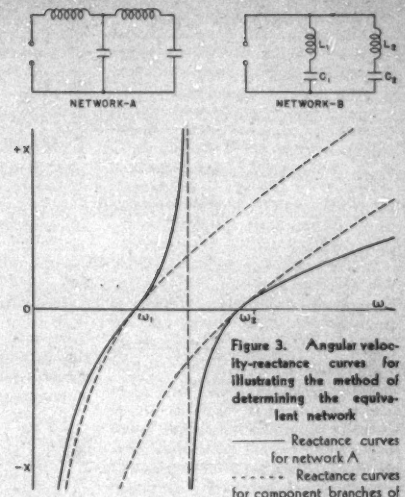


Figure 3. Angular velocity-reactance curves for illustrating the method of determining the equivalent network

——— Reactance curves for network A

- - - - - - Reactance curves for component branches of equivalent network B

By equating the coefficients of equations 5b and 6, the circuit elements of the equivalent network can be stated directly in terms of the zeros and slopes:

$$\sqrt{\frac{C_1}{L_1}}=\frac{2}{\omega_1\dfrac{\Delta X}{\Delta\omega_1}};\quad \sqrt{\frac{C_2}{L_2}}=\frac{2}{\omega_2\dfrac{\Delta X}{\Delta\omega_2}};\quad \cdots\sqrt{\frac{C_n}{L_n}}=\frac{2}{\omega_n\dfrac{\Delta X}{\Delta\omega_n}}$$

$$\omega_1=\frac{1}{\sqrt{L_1C_1}};\quad \omega_2=\frac{1}{\sqrt{L_2C_2}};\quad \cdots\omega_n=\frac{1}{\sqrt{L_nC_n}}$$

$$L_1=\frac{1}{2}\frac{\Delta X}{\Delta\omega_1};\quad L_2=\frac{1}{2}\frac{\Delta X}{\Delta\omega_2};\quad \cdots L_n=\frac{1}{2}\frac{\Delta X}{\Delta\omega_n}$$

$$C_1=\frac{1}{\omega_1{}^2L_1};\quad C_2=\frac{1}{\omega_2{}^2L_2};\quad \cdots C_n=\frac{1}{\omega_n{}^2L_n} \qquad (8)$$

These relations show that the circuit elements of the equivalent network can be determined directly from the angular velocity-reactance curves. This is graphically illustrated in Figure 3 for a simple two-mesh network. The reactance curves are shown for the original network and for each branch of the equivalent network. As the two networks are equivalent the reactance of network A is equal to the reactance of network B, which, of course, is equal to the parallel of the reactances of the individual branches. Each zero for the reactance of the total network occurs at the zero for a component branch and the corresponding slopes at these zeros are identical. This results from the fact that at the zero for one branch the reactance of the other branch becomes negligibly high in comparison with the branch under consideration. Thus, for each internal zero of the angular velocity-reactance curve there is an equivalent shunt branch containing L and C, the values of which are defined by the corresponding zero and slope. This same reasoning can be extended to any number of branches.

(b). Circuit-Opening Transients

The basic equivalent network in the series form of Table II can readily be derived from equation 4 for the response to unit current applied. For convenience this equation has been rewritten with the $e_o(t)$ term expanded as given in Table III:

$$e(t)=\frac{t}{C_s}+\left[\frac{L_s}{t}\right]_{t=0}+A_a\sin\omega_a t+A_b\sin\omega_b t\ldots+A_m\sin\omega_m t \qquad (9a)$$

$$=\frac{t}{C_s}+\left[\frac{L_s}{t}\right]_{t=0}+\frac{2}{\omega_a\dfrac{\Delta B}{\Delta\omega_a}}\sin\omega_a t+\frac{2}{\omega_b\dfrac{\Delta B}{\Delta\omega_b}}\sin\omega_b t\ldots+\frac{2}{\omega_m\dfrac{\Delta B}{\Delta\omega_m}}\sin\omega_m t \qquad (9b)$$

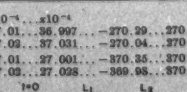
Table IV. Unit Voltage Applied

(1) ω	(2) ωL_2	(3) $1/\omega C_1$	(4) (2)+(3)	(5) 1/(4)	(6) ωC_1	(7) (5)+(6)	(8) 1/(7)	(9) ωL_1	Σ (8)+(9)
				x10⁻⁴	x10⁻⁴	x10⁻⁴			
2,701	2,701	−3,702.3	−1,001.3	9.987	27.01	36.997	−270.29	270.1	−0.19
2,702	2,702	−3,700.9	−998.9	10.011	27.03	37.031	−270.04	270.2	+0.16
3,701	3,701	−2,701.9	−999.1	10.009	37.01	27.001	−370.35	370.1	−0.25
3,702	3,702	−2,701.2	−1,000.8	9.992	37.03	27.028	−369.98	370.2	+0.22

$\omega_1=2{,}701$; $\Delta\omega_1=1.0$; $\Delta X=0.19+0.16=0.35$; $\frac{\Delta X}{\Delta\omega_1}=0.35$; $\frac{2}{\omega_1\frac{\Delta X}{\Delta\omega_1}}=0.00212$

$\omega_2=3{,}701$; $\Delta\omega_2=1.0$; $\Delta X=0.47$; $\frac{\Delta X}{\Delta\omega_2}=0.47$; $\frac{2}{\omega_2\frac{\Delta X}{\Delta\omega_2}}=0.00115$

$i(t)=0.00212\sin 2{,}701t+0.00115\sin 3{,}701t$

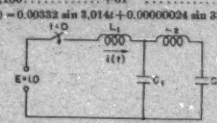


$L_1=0.1$ H; $L_2=1.0$ H; $C_1=1.0\,\mu$F; $C_2=0.1\,\mu$F

Table V. Unit Voltage Applied

ω	X	$\frac{\Delta X}{\Delta\omega}$
3,013	−0.17	
3,014	+0.03	0.20
33,100	+4,073	
33,200	+1,969	
33,179	−191	
33,180	+61	.252

$i(t) = 0.00332 \sin 3{,}014t + 0.00000024 \sin 33{,}179t$



The basic equivalent network of the series form is illustrated in Figure 2*b*. Each branch of this equivalent network corresponds to one term of the network solution given by equation 9. The L_a and C_a branches correspond to an equivalent inductance or an equivalent capacitance in series with the driving point, as defined in Table III. As the response of a simple parallel LC circuit to unit current is equal to $\sqrt{\frac{L}{C}} \sin \omega t$, where $\omega = \frac{1}{\sqrt{LC}}$, equation 9 can be written in the following form:

$$e(t) = \frac{t}{C_a} + \left[\frac{L_a}{t}\right]_{t=0} + \sqrt{\frac{L_a}{C_a}} \sin \omega_a t + \sqrt{\frac{L_b}{C_b}} \sin \omega_b t \ldots \sqrt{\frac{L_m}{C_m}} \sin \omega_m t \quad (10)$$

where

$$\omega_a = \frac{1}{\sqrt{L_a C}};\ \omega_b = \frac{1}{\sqrt{L_b C_b}};\ \ldots \omega_m = \frac{1}{\sqrt{L_m C_m}}$$

By equating the coefficients of equations 9*a* and 10, the remaining circuit elements of the equivalent network can be determined as follows:

$$\left.\begin{aligned} &A_a = \sqrt{\frac{L_a}{C_a}};\ A_b = \sqrt{\frac{L_b}{C_b}};\ \ldots A_m = \sqrt{\frac{L_m}{C_m}} \\ &\omega_a = \frac{1}{\sqrt{L_a C_a}};\ \omega_b = \frac{1}{\sqrt{L_b C_b}}; \\ &\qquad \ldots \omega_m = \frac{1}{\sqrt{L_m C_m}} \\ &C_a = \frac{1}{\omega_a A_a};\ C_b = \frac{1}{\omega_b A_b};\ \ldots C_m = \frac{1}{\omega_m A_m} \\ &L_a = \frac{A_a}{\omega_a};\ L_b = \frac{A_b}{\omega_b};\ \ldots L_m = \frac{A_m}{\omega_m} \end{aligned}\right\} \quad (11)$$

By equating coefficients of equations 9*b* and 10, the circuit elements of equivalent networks can be stated directly in terms of the zeros and slopes:

$$\left.\begin{aligned} &\sqrt{\frac{L_a}{C_a}} = \frac{2}{\omega_a \frac{\Delta B}{\Delta\omega_a}};\ \sqrt{\frac{L_b}{C_b}} = \frac{2}{\omega_b \frac{\Delta B}{\Delta\omega_b}}; \\ &\qquad \ldots \sqrt{\frac{L_m}{C_m}} = \frac{2}{\omega_m \frac{\Delta B}{\Delta\omega_m}} \\ &\omega_a = \frac{1}{\sqrt{L_a C_a}};\ \omega_b = \frac{1}{\sqrt{L_b C_b}}; \\ &\qquad \ldots \omega_m = \frac{1}{\sqrt{L_m C_m}} \\ &C_a = \frac{1}{2}\frac{\Delta B}{\Delta\omega_a};\ C_b = \frac{1}{2}\frac{\Delta B}{\Delta\omega_b};\ \ldots C_m = \frac{1}{2}\frac{\Delta B}{\Delta\omega_m} \\ &L_a = \frac{1}{\omega_a^2 C_a};\ L_b = \frac{1}{\omega_b^2 C_b};\ \ldots L_m = \frac{1}{\omega_m^2 C_m} \end{aligned}\right\} \quad (12)$$

In the preceding discussion the basic equivalent networks have been derived from network-response equations based on the Heaviside expansion theorem. By postulating that every network can be reduced to one of the basic forms of equivalent circuits, it is possible to derive the network response equations 3 and 4 without the use of the expansion theorem. Thus, the equivalent circuits provide not only a means of visualizing the network response but also the basis for an alternative derivation of the response equations.

Alternating Voltages and Currents Applied

The response of a network to alternating voltages or currents can be obtained from the response to unit voltage or current by superposition, or from the basic equivalent networks. The equations relating the alternating and unit-function responses have been derived and are included here for reference.

(a). Alternating Voltage Applied

Let

$$i(t) = \frac{t}{L_a} + \left[\frac{C_a}{t}\right]_{t=0} + \sum_{k=1}^{k=n} A_k \sin \omega_k t$$

be the network response to unit voltage. The response of the network to the sudden application of the voltage $E(t) = E \cos(\omega_s t + \phi)$ is then defined by the following equation:

$$\left.\begin{aligned} i(t) = &\left[\frac{E}{\omega_s L_a} \sin(\omega_s t + \phi) - \frac{E}{\omega_s L_a} \sin \phi\right] + \\ &\left[-E\omega_s C_a \sin(\omega_s t + \phi) + \left(\frac{EC_a \cos\phi}{t}\right)_{t=0}\right] + \\ &\left[-E\sum_{k=1}^{k=n} \frac{\omega_s \omega_k A_k}{(\omega_k^2 - \omega_s^2)} \sin(\omega_s t + \phi) + \right. \\ &\left. E\sum_{k=1}^{k=n} \frac{\omega_k^2 A_k}{(\omega_k^2 - \omega_s^2)}\left(\cos\phi \sin \omega_k t + \frac{\omega_s}{\omega_k} \sin\phi \cos \omega_k t\right)\right] \end{aligned}\right\} \quad (13)$$

Each of the bracketed terms in the preceding equation is the a-c solution corresponding to one term in the unit voltage response equation or for one branch of the equivalent network. The first term in each bracket is a component of the steady-state response of the network, whereas the second term is in each case a transient response. In many cases less work is involved in determining the steady-state response directly from the network reactance at $\omega = \omega_s$. If this reactance is equal to $X(j\omega_s)$, then the steady-state response is equal to

$$\frac{E}{X(j\omega_s)} \cos(\omega_s t + \phi)$$

Table VI. Alternating Current Applied

(1) ω	(2) ωL_2	(3) $1/\omega C_2$	(4) (2)+(3)	(5) $1/(4)$	(6) ωC_1	(7) $1/\omega L_1$	8 (5)+(6)+(7)
				$\times 10^{-4}$	$\times 10^{-4}$	$\times 10^{-4}$	$\times 10^{-4}$
2,701	2,701	−3,702.30	−1,001.30	9.987	37.01	−37.023	−0.026
2,702	2,702	−3,700.96	−998.96	10.011	37.02	−37.009	+0.021
3,701	3,701	−2,701.97	999.03	10.009	37.01	−27.019	−0.018
3,702	3,702	−2,701.24	1,000.80	−9.992	37.02	−27.012	+0.016
377	377	−26,500	−26,100	0.383	3.77	−265	−261

$\omega_a = 2{,}701$ $\omega_b = 3{,}701$

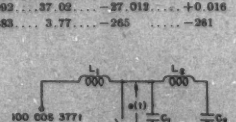
$\frac{\Delta B}{\Delta\omega_a} = 0.047 \times 10^{-4}$ $\frac{\Delta B}{\Delta\omega_b} = 0.034 \times 10^{-4}$

$A_a = 157$ $A_b = 150$

Fault current $= \frac{100}{j37.7} \cos 377t$

$= 2.65 \cos\left(377t - \frac{\pi}{2}\right)$

$I(t) = 2.65 \cos\left(377t - \frac{\pi}{2}\right)$



Steady-state component of $e(t) = \frac{2.65}{-j0.0261} \cos\left(377t - \frac{\pi}{2}\right) = 102 \cos 377t$

$e(t) = 102 \cos 377t - 89 \cos 2{,}701t - 44 \cos 3{,}701t$

(b). Alternating Current Applied

Let

$$e(t) = \frac{1}{C_s} + \left[\frac{L_s}{1}\right]_{t=0} + \sum_{k=1}^{k=n} A_k \sin \omega_k t$$

be the response for unit current applied. The network response to the current $I(t) = I \cos(\omega_o t + \phi)$ is then defined by the following relations:

$$\left.\begin{aligned} e(t) = &\left[\frac{I}{\omega_o C_s} \sin(\omega_o t + \phi) - \frac{I}{\omega_o C_s} \sin \phi\right] + \\ &\left[-I\omega_o L_s \sin(\omega_o t + \phi) + \left(\frac{IL_s \cos \phi}{1}\right)_{t=0}\right] + \\ &\left[-I \sum_{k=1}^{k=n} \frac{\omega_k \omega_o A_k}{(\omega_k^2 - \omega_o^2)} \sin(\omega_o t + \phi) + \right. \\ &I \sum_{k=1}^{k=n} \frac{\omega_k^2 A_k}{(\omega_k^2 - \omega_o^2)} \left(\cos \phi \sin \omega_k t + \right. \\ &\left.\left. \frac{\omega_o}{\omega_k} \sin \phi \cos \omega_k t\right)\right] \end{aligned}\right\} \quad (14)$$

Each of the bracketed terms in the preceding equation is the a-c solution corresponding to one term of the response equation for unit current applied, or for one branch of the equivalent network. The first term in each bracket is the steady-state response, and the second term is the transient response. The steady-state response can also be obtained from the network admittance for $\omega = \omega_o$. If this admittance is represented by $B(j\omega_o)$, the steady-state response is equal to

$$\frac{I}{B(j\omega_o)} \cos(\omega_o t + \phi)$$

One special case of the foregoing solution is of general interest, the case where the applied current is equal to $I \sin \omega_o t = I \cos(\omega t - \pi/2)$:

$$\left.\begin{aligned} e(t) = &\left[-\frac{E}{\omega_o C_s} \cos \omega_o t + \frac{I}{\omega_o C_s}\right] + \\ &\left[I\omega_o L_s \cos \omega_o t\right] + \\ &\left[I \sum_{k=1}^{k=n} \frac{\omega_k \omega_o A_k}{(\omega_k^2 - \omega_o^2)} \cos \omega_o t - \right. \\ &\left. I \sum_{k=1}^{k=n} \frac{\omega_k \omega_o A_k}{(\omega_k^2 - \omega_o^2)} \cos \omega_k t\right] \end{aligned}\right\} \quad (15)$$

Illustrative Examples

The method of analysis just described is illustrated in Table IV for a relatively simple circuit. The problem in this case is to find an analytical expression for the current in the inductance L_1 when unit voltage is suddenly applied to the driving-point terminals. The zeros are first located approximately by rough slide-rule calculations, preferably using a plot of the reactance curve as a guide. The reactance of the circuit, as viewed from the driving point, is calculated by combining the reactance of the individual branches as illustrated in the table. It should be noted that it is not necessary to obtain the complete reactance curve but only those parts of the curve in the vicinity of zero reactance. Only two points near each zero are included in the illustration, these points having been arrived at after other preliminary points were obtained. The reactance curves need not be plotted except as a guide; all necessary information is included in the tabulated data. In this example $\Delta\omega$ was taken as one radian per second in order to obtain an accurate evaluation of $\Delta X/\Delta\omega$. The angular velocity increment to use in any particular case depends upon the network characteristics and upon the accuracy desired. It should be stressed that the reactance calculations should be carried out to a high degree of accuracy if a high degree of accuracy is desired in the final network response. However, if practical engineering accuracy is sufficient then less accuracy is required in calculating the reactances.

After the zeros and slopes are obtained the response is calculated by substituting these values in equation 3. As the network considered in this example is of type I, $i_o(t)$ is equal to zero and so the complete response is as given at the bottom of Table IV.

The accuracy of the method can readily be checked by noting the initial conditions. At $t = 0$, the voltage across C_1 is zero, so the applied unit voltage must be consumed across L_1, that is, $L_1 \frac{di(t)}{dt}$ should be equal to unity at $t = 0$. For Table IV, the check gives

$$L_1 \frac{di(t)}{dt} = 0.1(2{,}701 \times 0.00212 + 3{,}701 \times 0.00115) = 0.998 \text{ at } t = 0$$

which is accurate to within 0.2 of one per cent.

In the general case the calculated responses for networks of types I and II are checked by noting that $L_s \frac{di(t)}{dt} = 1.0$ at $t = 0$, assuming unit voltage applied, where L_s is the equivalent inductance between the driving-point terminals with all capacitances short-circuited.

In special cases some difficulty may be experienced in locating the zeros. For example, the reactance of the network in Table V was calculated at $\omega = 33{,}100$ and 33,200 and the resulting reactances were both positive and decreasing in magnitude. These results incorrectly may be assumed to indicate that a zero would be present at some higher angular velocity, whereas the zero is actually between these values of angular velocity. When such cases are encountered much time is usually required to locate the zero. However, when the zeros are hard to locate, the slope of the reactance curve is large and as a result the transient current corresponding to the zero may be an unimportant component of the network response. In Table V the second component of current is only 0.00723 per cent of the first component and so is insignificant. This situation could have been predicted by checking the first component of current with the initial conditions. Neglecting the second term,

$$L_1 \frac{di(t)}{dt} = 0.1(0.00332)(3{,}014) = 1.0 \text{ at } t = 0$$

which satisfies the boundary conditions. It is very helpful to make these checks for each component as soon as it is obtained, in order to obtain not only a check on the integrity of the calculation but also a continuous indication of the relative importance of the remaining terms of the solution.

The problem of calculating the transient voltage following the sudden opening of a switch can be treated in terms of a suddenly applied current. Considering the network in Table VI, the current flowing in the closed switch is equal to $+2.65 \sin 377t$. The current in the switch can be reduced to zero, which is equivalent to opening the switch, by inserting a current $+2.65 \sin 377t$ in a direction opposite to the initial current. In making the calculations with the method of zeros and slopes, the response to unit current is first obtained, as illustrated in Table VI, by determining the zeros and slopes of the susceptance curves. The response to the current $+2.65 \sin 377t$ is then found by using the relations given in part *b* of the preceding section. The steady-state component of the recovery voltage was found by first calculating the network susceptance at $\omega = 377$.

Extensions of the Method

In the paper the calculating procedure has been illustrated only for the zeros and slopes derived from the constants of the networks. However, it is possible and sometimes convenient to form the analytical expression for the impedance (or admittance) function and its derivative and to use the first or both of these to determine the zeros and slopes. The method of analysis and calculating procedure have been discussed only for prob-

lems involving driving-point functions. However, they are also applicable to problems involving transfer functions, for example, the determination of current in a particular branch of a network resulting from the application of potential to the driving-point terminals. The procedure is the same except that for the latter case the zeros and slopes are obtained from the transfer function instead of the driving-point function. Angular velocity-reactance (or susceptance) curves, derived from measurements on a miniature-system setup or even from an actual system instead of from calculated data as described in the paper, can be used for the determination of zeros and slopes.

Appendix

The response of a network to a suddenly applied unit voltage is given by the Heaviside expansion theorem as follows:

$$i(t) = i_0(t) + \sum_{k=1}^{k=2n} \frac{e^{p_k t}}{p_k Z'(p_k)} \qquad (1)$$

In this form of the expansion theorem the function $i_0(t)$ defines the steady-state network solution and that part of the transient solution determined by the external zeros. Referring to the second term, $Z(p)$ is the impedance function of the network as viewed from the driving point and $Z'(p)$ is the first derivative of the impedance function with respect to p. The summation indicates that there are as many terms in the transient solution (neglecting the $i_0(t)$ term) as there are roots of the equation $Z(p) = 0$. The quantity p_k is a general expression for the roots of $Z(p) = 0$.

In a no-loss network the roots of $Z(p) = 0$ are pure imaginaries appearing in conjugate pairs and so can be represented by $p = \pm j\omega$. It should also be noted that in no-loss network $Z'(j\omega_k) = Z'(-j\omega_k)$. Substituting these relations into the expansion theorem reduces equation 1 to

$$i(t) = i_0(t) + \sum_{k=1}^{k=n} \frac{e^{j\omega_k t}}{j\omega_k Z'(j\omega_k)} - \sum_{k=1}^{k=n} \frac{e^{-j\omega_k t}}{j\omega_k Z'(j\omega_k)} \qquad (2)$$

This form of the theorem can then be converted to the trigonometric form, remembering that

$$\frac{e^{j\omega t} - e^{-j\omega t}}{2j} = \sin \omega t,$$

$$i(t) = i_0(t) + \sum_{k=1}^{k=n} \frac{2}{\omega_k Z'(j\omega_k)} \sin \omega_k t \qquad (3)$$

In a no-loss network $Z(j\omega)$ is recognized as the alternating-current reactance of the network as measured at the driving point, and $\omega_2 = \omega_1, \omega_2 \ldots n$ are the angular velocities that give zero reactance. The term $Z'(j\omega)$ is, therefore, the slope of the reactance curve plotted as a function of $j\omega$, and $Z'(j\omega_2)$ is the slope at $\omega = \omega_2$. It becomes apparent, therefore, that the constants of integration, or the coefficients of the series of sine functions, depend only on the angular velocities resulting in zero reactance, and on the slope of the reactance curve at these corresponding velocities.

In making numerical computations, equation 3 is more useful in its approximate form,

$$i(t) = i_0(t) + \sum_{k=1}^{k=n} \frac{2}{\omega_k \dfrac{\Delta X}{\Delta \omega_k}} \sin \omega_k t \qquad (4)$$

or with alternative notation,

$$i(t) = i_0(t) + A_1 \sin \omega_1 t + A_2 \sin \omega_2 t + \ldots A_n \sin \omega_n t \qquad (5)$$

where

$$A_1 = \frac{2}{\omega_1 \Delta X / \Delta \omega_1}; \quad A_2 = \frac{2}{\omega_2 \Delta X / \Delta \omega_2}; \ldots$$

$$A_n = \frac{2}{\omega_n \Delta X / \Delta \omega_n}$$

The Cause and Control of Some Types of Switching Surges

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AMONG the several causes other than lightning which can result in power-system overvoltages, switching surges rank high in importance. In the past the magnitudes of switching surges have been considered on a statistical basis, but the need for frequent switching operations naturally led to their study and to analyses of their causes and magnitudes.

Switching surges are transient overvoltages caused by closing or opening a circuit and can vary in magnitude and duration over wide ranges. As contrasted with lightning surges which are generally impulsive and unidirectional in character, switching surges are oscillatory in nature, of frequency anywhere from very high to fundamental or subharmonic frequency, and of duration from a small portion of a cycle to a relatively long time which may be governed by the time between the opening or closing of successive phases on a three-phase system. Where steepness of voltage wave front is a consideration, it should be recognized that surges caused by switching on certain circuits may have wave fronts steeper than the ordinary lightning surge.

Switching in circuits supplying ungrounded transformer banks can result in high voltages during the switching period if the interval between closing or opening the first and last phase in a three-phase system is long enough for the intermediate steady-state voltage conditions to be attained. This condition may obtain during single-phase switching on a three-phase system, or when one or two conductors are open by virtue of conductor breaks or blown fuses. The voltages obtained under these conditions have been studied and reported[1] for a wide range of constants. The principal constants which apply are the transformer magnetizing reactance, the system capacitance between the switch and the transformer, and the degree of transformer saturation. This paper in general, will, consider over-voltages other than these, which occur even with reasonably simultaneous action of the switches in the three poles. Primary consideration will be given to transient voltages caused by normal rather than fault switching operations.

Conclusions Drawn

Some of the conclusions which may be drawn from the analyses and discussion are as follows:

1. When a switch on an unfaulted power system is being closed, transient voltages as

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high as nearly twice normal line-to-neutral voltage may be obtained. This assumes that closing of the three poles of the switch is reasonably simultaneous, as would be true of the ordinary circuit breaker.

2. Transformer windings can be very effective in discharging the stored energy of a capacitive circuit being opened and thus reduce the possibility and magnitude of restriking overvoltages.

If the breaker is connected to the line, cable, or capacitor bank through a delta-wye-grounded transformer bank as shown in Figure 3B, the overvoltage under restriking conditions will be limited to less than twice normal line-to-ground voltage if the transformer has a kilovolt-ampere rating equal to or greater than the charging kilovolt-amperes of the capacitive circuit. Simultaneous clearing of the three phases is not required for this statement to hold true.

Where switching is done at line voltage, transformer windings switched with the line, as shown in Figure 3A, are also effective if the ratio of the capacitive reactance being switched to the transformer magnetizing reactance, both on a line-to-neutral basis (this may be considered the ratio of transformer magnetizing kilovolt-amperes to capacitance kilovolt-amperes), falls between the approximate limits of 0.0012 and 0.02 or 0.45 and ∞. In the region between 0.02 and 0.45, reasonably simultaneous opening of the three phases is essential to keeping the switching surge voltages low.

3. The prevention of overvoltages of harmful magnitudes, which may occur in certain limited fields on account of the forcing of the current zero by the circuit breaker on interrupting, may be accomplished by the use of shunt capacitors. The minimum capacitor kilovolt-ampere value for satisfactory performance depends upon the characteristics of the circuit, and the breaker, and the allowable overvoltage magnitude.

It is not intended to convey the impression that in every case of switching capacitive circuits or of switching magnetizing currents, special means need be used to prevent serious switching surge overvoltage. Although restriking may occur while opening capacitive circuits, such restriking will not necessarily produce overvoltages serious from the standpoint of circuit and apparatus insulation, particularly where adequate lightning-arrester protection is employed. This also is true of overvoltages produced by off-zero magnetizing-current interruption.

Switch-Closing Overvoltages

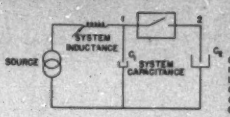
When an unenergized circuit is suddenly connected to an energized one, a voltage oscillation of twice (neglecting damping caused by losses) the voltage difference between them at the instant before closing occurs immediately following the closing operation. The reason for this is the presence of system capacitance, and it may be illustrated by Figure 1A which shows a one-line diagram of a system, a switch, and a capacitor. Assuming that the switch is closed at the peak of the generated voltage wave, a, in figure 1B, the voltage at point 1 instantaneously drops to a value given by

$$E_1 = \frac{EC_1}{C_1 + C_2}$$

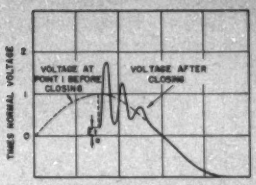
and an oscillation of voltage of amplitude $E - E_1$ then takes place about the fundamental voltages as shown, rapidly decaying, in general, because of losses and other system damping such as loads. The oscillation frequency is determined by the system inductance and total capacitance.

In the limit, if C_1 is reduced to zero, E_1 becomes zero, the oscillation amplitude becomes E, and the total voltage on the capacitor reaches $2E$, if the switch is closed at the voltage peak and damping is neglected.

It has been shown[3] that, if the capacitance being switched, C_2, in Figure 1A, is replaced by a line of distributed inductance and capacitance, a similar voltage oscillation will appear all along the line. In the case of the line, however, the oscillation will appear at various points along the line at successive intervals of time and will require a time to reach the far end, depending primarily on the line length and its inductance and capacitance per unit of length. The frequency of the oscillation is also governed by these quantities.



A. Equivalent circuit of system, switch, and a capacitance



B. Voltage transient on closing switch of Figure 1A at normal voltage crest

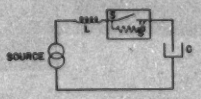
Figure 1. Illustrating switch-closing transient

Switch-Opening Overvoltages—Interrupter Restriking

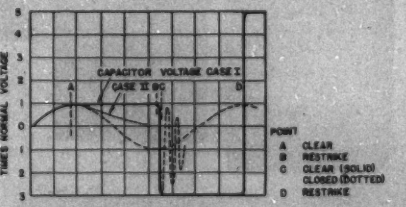
Switch-opening transients are generally negligible if the interrupter opens the circuit at or very near current zero and does not restrike. Restriking takes place in any interrupter if the voltage across its contacts following an interruption recovers more rapidly than the dielectric strength of the insulating medium. When a fault on a solidly grounded system having small capacitance is being cleared by an interrupter, it may restrike several times following an attempted clearing at a current zero, until the contacts have gotten sufficiently far apart that they can withstand the recovery voltage transient of less than twice normal crest line-to-ground voltage, which will occur at each attempted clearing. This restriking is normal and expected and is not harmful either to the breaker or the system. (On a reactance-grounded system, restriking when clearing unbalanced faults can result in severe overvoltages if the ratios of zero-to-positive-sequence inductive reactance are high.[2])

However, under certain conditions, overvoltages of a serious nature may occur as a result of delayed restriking when opening the normally low balanced charging current of capacitance circuits, notably transmission lines and large banks of capacitors. The results of recent studies on capacitor[4] and transmission-line[5] switching, in which this phenomenon has been analyzed, have been reported. For the sake of completeness, a brief discussion of the mechanism by which these overvoltages are obtained follows.

Referring to Figure 2A which represents

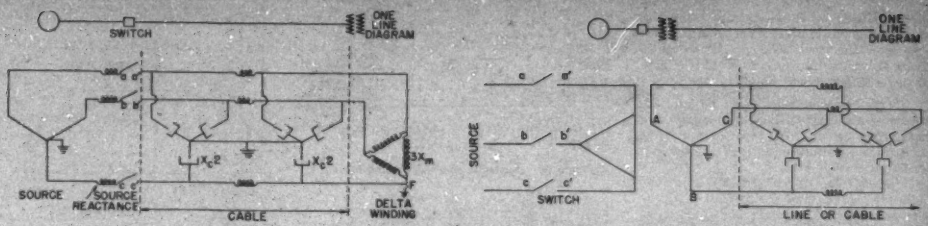


A. Equivalent circuit of system, switch, and a capacitance



B. Voltage transient resulting from a restrike of switch in Figure 2A 180 electrical degrees after interruption at normal current zero (voltage crest)
Case I—Without resistor across switch
Case II—With resistor across switch, final interruption by opening switch S' of Figure 2A

Figure 2. Illustrating transient voltage resulting from restriking when opening a capacitive circuit



A. Three-phase cable circuit with saturable delta winding switched together

B. Three-phase cable circuit with delta–wye-grounded transformer between switch and cable

Figure 3. Miniature-system (transient-analyzer) connection diagrams

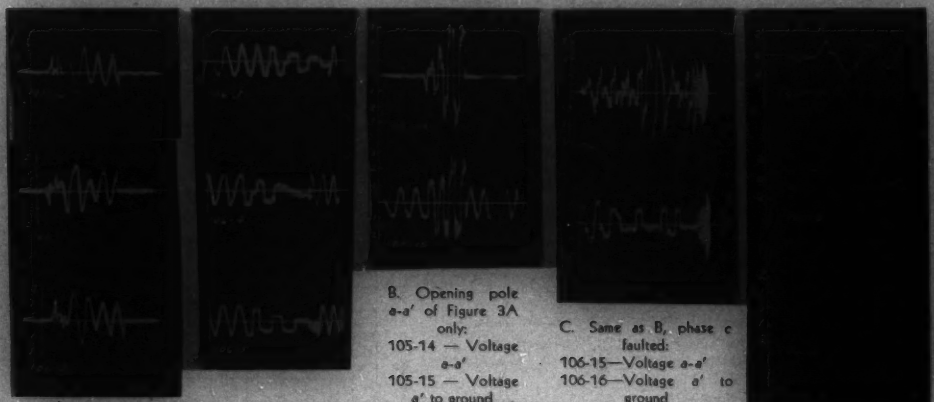
one phase of a system of inductance L supplying a capacitance load, C, let switch S be opened. At a current zero (voltage crest point A of Figure 2B), the current will be interrupted, leaving a full charge on the capacitor. The voltage across the interrupter contacts will grow from zero to twice normal in 180 electrical degrees, as shown by the difference of the stored capacitor charge and the system normal frequency voltage. If restriking occurs during this period, a voltage oscillation will result of magnitude equal to the switch voltage, about the fundamental, resulting in a total voltage of nearly three times normal (neglecting damping) if the restrike occurs when the switch volts are a maximum, as shown at point B. The oscillation will be at natural frequency, and at its first peak (point C), the arc current will be zero. If conditions within the interrupter are conducive to the arc's remaining extinguished at this point, the switch voltage will grow from twice to four times normal in the next 180 degrees, and a restrike at point D would result in a voltage of nearly five times normal. If the arc does not go out at C, the natural frequency voltage will gradually decay as shown by the dashed curve.

It should be remembered that whether the interrupter will restrike under this switching condition depends upon the magnitude of the capacitance current being interrupted and the interrupter characteristics. Tests[4] have established the amount of capacitance, in terms of kilovolt-amperes, that certain breakers in the voltage class 15 kv and below may interrupt with reasonable assurance against delayed restriking. Perhaps future tests will be desirable at higher voltages.

A study of Figure 2B indicates that whatever may be done to reduce the charge stored on the capacitor or line after the first clearing will help very materially, not only to prevent restriking when switching capacitive circuits, but also to reduce greatly the magnitude of the overvoltage obtaining if restriking does occur. The following paragraphs in this section will be devoted to discussing the various means which may be employed to bring about a reduction in the capacitor or line voltage within the half-cycle following the first interruption of the circuit.

1. Resistor Switching

If, when the switch S of Figure 2A is opened, a relatively high resistance is



A. Opening all poles of Figure 3A, ideal clearing:
105-16—Voltage a-a'
106-11—Voltage b-b'
106-2—Voltage c-c'
106-3—Voltage a' to ground
106-4—Voltage b' to ground
106-5—Voltage c' to ground

B. Opening pole a-a' of Figure 3A only:
105-14 — Voltage a-a'
105-15 — Voltage a' to ground

C. Same as B, phase c faulted:
106-15—Voltage a-a'
106-16—Voltage a' to ground

D. Opening pole a-a' of Figure 3B:
100-9 —Volts a-a'
100-10—Volts a' to ground
100-11—Volts C to ground

Figure 4. Transient-analyzer oscillograms

All calibrations in times normal line-to-neutral voltage

inserted in the circuit by this action, as would be the case if the interrupter were shunted by a resistor as shown by the dotted lines, the capacitance is afforded a discharge path through sufficient resistance to permit considerable decay of its voltage as shown in Figure 2B, case II (dotted curve). This scheme not only reduces the possible overvoltages but also affords a relatively easy subsequent interruption of the circuit by switch S', because, since the resistor ohms are relatively high, the current will be nearly in phase with the voltage, the current will be small, and at current zero the circuit voltage will be near zero.

Reference 5 describes tests and analyses of an oil circuit breaker provided with such a resistor for reducing the overvoltage hazard when interrupting a long high-voltage line, and reference 2 similarly indicates performance of a breaker provided with resistors to assist in switching a large 13.8-kv capacitor bank. Reference 5 shows that it is possible to obtain a practical value of contact shunting resistance which will provide a very satisfactory means of solving the capacitance switching problem. It should not be inferred, however, that all existing breakers for switching long high-voltage lines need be provided with resistors.

2. Discharge Through Transformer Windings

In the case where, after the switch is opened, the capacitor or line is left with a transformer bank in shunt with it, the windings provide a discharge path for the energy stored in the capacitance. The effectiveness of the windings depends upon their size and whether they are delta—or grounded-wye—connected to the line.

(*a*). *Delta or Ungrounded-Wye Windings.* Refer to Figure 3A. This shows the connection diagram of a miniature-system representation of a cable having a total equivalent shunt capacitive reactance per phase of X_c ohms with the delta winding of an unloaded transformer connected to it. The transformer has a magnetizing reactance per phase of X_m on a line-to-neutral basis. As the first pole of the interrupter a-a' opens, the cable capacitance begins to discharge through the transformer, thus reducing the voltage across the switch initially, over the case of the cable or line alone. If the remaining poles of the interrupter subsequently clear "ideally"—each at its nearest available current zero, the switch voltage (across a-a') will never reach twice normal, and the tendency of the interrupter to restrike should be markedly reduced.

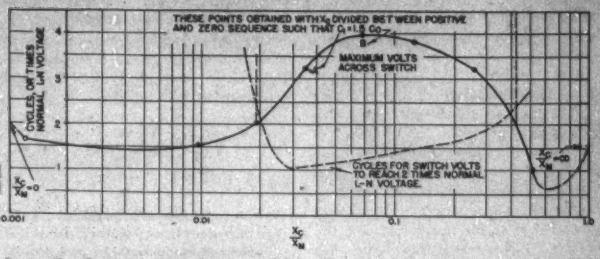

THESE POINTS OBTAINED WITH X_0 DIVIDED BETWEEN POSITIVE AND ZERO SEQUENCE SUCH THAT $C_0 = 1.2\ C_{0-n}$
MAXIMUM VOLTS ACROSS SWITCH
CYCLES FOR SWITCH VOLTS TO REACH 2 TIMES NORMAL L-N VOLTAGE.
CYCLES, OR TIMES NORMAL L-N VOLTAGE
$\frac{X_c}{X_m}=0$
$\frac{X_c}{X_m}=\infty$
0.001
0.01
0.1
1.0
$\frac{X_c}{X_m}$

Figure 5. Summary of maximum switch voltages and time for switch voltage to reach twice normal line-to-neutral voltage when opening switch a-a' of Figure 3A for various values of X_c/X_m

Oscillograms 105-16 through 106-5 of Figure 4 show switch and cable voltages for the case of ideal clearing for a ratio of $X_c/X_m = 0.052$. If the interval of time between successive pole clearings is too large, however, the switch and cable voltages may, depending upon the ratio X_c/X_m, become much larger than twice normal, because of series resonance between the capacitance of the unopened conductors and the saturable transformer reactance. These are the overvoltages mentioned previously and reported in reference 1. The time required for the switch voltage to reach twice normal again depends on the ratio X_c/X_m and is summarized for the first pole to clear in curve form, Figure 5, together with the steady-state values that the switch voltage will attain for various values of the ratios. Oscillogram 105-14 shows the voltage across the first pole (a-a') opening with the others remaining closed for a ratio of $X_c/X_m = 0.052$. Oscillogram 105-15 gives the voltage of point a' to ground for this condition of interruption. It will be noted that it required about one cycle for voltage a-a' to reach twice normal line-to-neutral value, and, if reasonably simultaneous clearing of the other poles had occurred, pole a would have had a comparatively low voltage across it while opening. On the basis that similar results were obtained on the other poles, it was considered adequate to use the transient resulting from the first pole to open as a general criterion of the effectiveness of a delta winding to prevent the switch voltage from reaching at least twice normal in a short time. Also, only a general indication of results was necessary, since in general long times between successive pole openings cannot be tolerated.

It was interesting to note that, if a ground fault on one of the cable or capacitor phases as shown by F in figure 3A was being cleared, the transient voltages resulting from clearing the first of the unfaulted poles are somewhat reduced from the case of no fault. The reason for this is that a discharge path for the capacitance in addition to the delta winding exists by virtue of the fault. Oscillogram 106-15 shows the switch voltage (a-a') for $X_c/X_m = 0.052$ for the condition of phase a being cleared, with a fault on phase c, and 106-16 shows the voltage of a' to ground for this condition.

The data in Figure 5 is for the condition of equal positive- and zero-sequence capacitances. To show the effect of a ratio of positive-to-zero-sequence capacitance of 3/2 (approximately the value for an overhead line), tests were made on the miniature system which indicated the effect to be one of moving the curves of Figure 5 slightly to the right.

(*b*). *Grounded-Wye Windings.* If the line or grounded-neutral capacitor is left with a grounded winding instead of an ungrounded one, it will be somewhat more effective than an ungrounded one, because it is capable of discharging both zero- and positive-sequence capacitance. A special case where a delta–wye-grounded transformer is interposed between the interrupter and line with the line or capacitor connected to the wye-grounded winding was investigated. Figure 3B shows the miniature-system connections. The case of a transformer large enough to carry the line-charging or capacitor kilovolt-amperes being interrupted alone resulted in voltages of less than twice normal from line to ground even with a restrike applied at a time when the switch voltage following first clearing was a maximum. Oscillograms 100-9 to -11 show miniature-system voltages for this case. This indicates the benefits to be gained by "low-side switching" of lines, cables, or capacitors.

Switch-Opening Overvoltages—Interruption Off Current Zero

Another means by which an overvoltage may be obtained on opening a circuit

is the studden stoppage of current flow before a normal-frequency current zero has arrived. Under this condition, the voltage obtainable is controlled by the circuit inductance and the rate of change of current caused by the interrupter thus forcing current zero. Overvoltages of this nature have been encountered in the process of interrupting transformer magnetizing currents which are small in magnitude, compared to the normal load current of both the transformer and the breaker. In particular, this problem has been encountered in connection with arc-furnace transformers which, because they are switched at no load frequently, are more apt to be subjected to this type of switching surge than other transformers, other things being equal.

Here again the tendency for the overvoltage to occur is dependent upon the characteristics of the interrupter at the magnitude of current to be switched. For a particular value of current a given interrupter might break the circuit at current peak (worst case), at or near zero, or anywhere in between.

Lightning arresters can be and have been used to protect transformers from this type of overvoltage, but it should be recognized that, if the interrupter cuts off at too high a current, the energy (LI^2) stored in the transformer may be greater than the arrester can dissipate without damage to itself.

An obvious means of preventing the possibility of this type of switching-surge overvoltage is to supply the magnetizing kilovolt-amperes of the transformer by means of capacitors, and switching the two together. The only no-load current to be switched if complete compensation is provided is loss current, which will be very small. It is not particularly important in this method whether either the transformer winding or the capacitor neutral is grounded.

Analysis (see appendix) and miniature-system tests indicate that it is not necessary to supply entirely the transformer magnetizing kilovolt-amperes in order to limit the transient voltage to acceptable values. In the appendix it is shown that for the circuit of Figure 6, representing a transformer winding protected by a capacitor, assuming interruption at current crest (worst case) gives a voltage oscillation across the transformer-capacitor combination whose equation is

$$E_p = -E\sqrt{\frac{X_c}{X_m}}\sin\left\{\sqrt{\frac{X_c}{X_m}}t\right\}$$

where

E = normal line-to-neutral voltage
X_c = capacitor line-to-neutral ohms per phase at fundamental frequency
X_m = transformer magnetizing line-to-neutral ohms per phase at fundamental frequency and normal voltage

The expression $\sqrt{X_c/X_m}$ may be written

$$\sqrt{\frac{\text{transformer magnetizing kilovolt-amperes}}{\text{capacitor kilovolt-amperes}}}$$

and gives the crest value of the voltage oscillation following interruption and the order of its natural frequency. Thus a capacitor kilovolt-ampere of 25 per cent of the transformer magnetizing kilovolt-amperes will limit the overvoltage under the worst condition of interruption, at current crest, to twice normal, and the oscillation will be at second harmonic frequency.

Although this analysis is made on the basis of an equivalent single-phase circuit with saturation of the transformer neglected, miniature-system tests on a three-phase setup including saturation indicates that the results obtained apply practically whether the transformer and/or the protective capacitors are grounded or ungrounded.

Appendix—Magnetizing-Current Interruption Off Zero

In the equivalent circuit of Figure 6, in which a shunt capacitor is connected to the terminals of the transformer, let

$$\text{Per unit transformer magnetizing kilovolt-amperes} = \text{kva}_m = \frac{1}{X_m}$$

$$\text{Per unit capacitor kilovolt-amperes} = \text{kva}_c = \frac{1}{X_c}$$

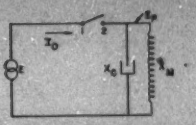


Figure 6. Equivalent circuit of a source, a switch, and an unloaded transformer shunted by a protective capacitor

The current flowing before the switch is opened is

$$I_0 = \frac{E(X_c - X_m)}{X_c X_m}$$

Assuming interruption at current crest (worst case), this may be represented mathematically by inserting the negative of this current through the switch, letting $t=0$ at current crest and the switch voltage will be $I_c \cos \omega t Z(p) = E_{12}$. The voltage across the transformer-capacitor combination is

$$E_p = E + E_{12}$$
$$= E \sin \omega t + I_0 \cos \omega t Z(p)$$

in operational form this is, where

$$\omega^2 = \frac{1}{CL}$$

$$E_p = \frac{E\omega p}{p^2+\omega^2} 1 + I_0 \frac{\omega^2 p^2}{(p^2+\omega^2)} \times \frac{pL}{(p^2+\omega^2)} 1$$

And the solution of this is

$$E_p = E \sin \omega t - \frac{I_0 L \omega^2 \omega}{(\omega^2 - \omega^2)}\left[\sin \omega t - \frac{\omega_0}{\omega} \sin \omega t\right]$$

which reduces to

$$E_p = -E\sqrt{\frac{X_c}{X_m}}\sin\left(\sqrt{\frac{X_c}{X_m}}t\right)$$

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Automatic Voltage Compensator for Resistance Welding Control

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AMONG the more recent developments in a-c resistance welding control is the voltage compensator. This compensator is an auxiliary control used in conjunction with a standard type of phase-controlled welding panel, the circuit of which is shown in Figure 1. The function of the voltage compensator is to maintain the weld current substantially constant irrespective of line-voltage variations. The inability to obtain new feeders and the burden of added loads in war plants have in many cases made the power systems incapable of supplying several welding machines simultaneously without experiencing an appreciable drop in line voltage. Welding heat, which varies with current squared, will be reduced by 19 per cent for a ten per cent drop in line voltage; a line drop of 20 per cent will reduce the welding heat 36 per cent which is intolerable for consistent welding. These conditions can be remedied by the addition of a small inexpensive auxiliary control, such as the voltage compensator. The regulation of many overworked high reactance welding feeders can then be tolerated because consistent welds will be produced, whereas without proper compensation, poor welds would inevitably result. A compensator unit is shown in Figure 2 installed just in front of the current transformer in the bottom of a portable welding-machine control panel.

Requirements of the Compensator

First, let us consider where the compensator is required. Small voltage variations are permissible, since welding pressure, electrode shape, metallic finishes and other conditions may vary to some degree. Information in previous papers indicates that a five per cent voltage variation will not seriously reduce the weld strength of many types of steel.[1,2] Heavier line drops will probably require the voltage compensator. Its chief utility is on lines having more than one welding machine, since the line drop can be taken into account when adjusting current for one machine. Where line voltage drifts up and down, the compensator becomes advantageous with just one machine.

The next requirement is that the control operate entirely automatically. In operation, any gradual drift of the power-supply voltage will be continuously corrected, so that upon initiation of a spot weld, the initial cycles automatically start at the corrected heat setting. It is also important that the transient rate of response to sudden voltage changes should be as rapid as possible. This rapid response is very necessary in adapting such a control to seam and short-timed spot welding, where a slow response would result in relatively large variations between spots. It is, therefore, equally important that this voltage compensator be capable of nullifying the effects of transient as well as gradual power-supply fluctuations.

Other desirable features include simplicity, ease of connecting and adjustment, and, finally, low cost.

Phase-Controlled Welding Circuits

In order to understand how this voltage compensator works, it will be advantageous to review a standard phase-controlled welding circuit. Common to all electronic a-c welding control circuits are two power tubes, usually of the ignitron type, which are connected in an inverse parallel or back-to-back arrangement as shown in Figure 3. The function of these tubes is to serve as an electronic switch in controlling the power delivered to the welding machine. In this two-tube arrangement a-c power may be passed, since one tube may be rendered conductive in one direction, while the other tube, connected in reverse manner, permits conduction in the other direction. To render an ignitron conductive, a current must be passed through its ignitor or control element. This firing current is furnished by a thyratron-type tube which is capable of delivering high currents for short intervals. The welding control is designed to control these firing tubes, which in turn render the power tubes conductive.

When phase control is added to this electronic switch, the point at which this conduction is initiated is varied so that the power tubes carry current for a given preset portion of each half cycle. The particular phase-control circuit to which the line-voltage compensator was applied is shown in an elementary manner in Figure 1. For simplicity, all grid to cathode capacitors and transient arresting resistors have been left out. The net grid bias voltage on the firing tubes (see Figures 3 and 4) is the sum of four separate voltages:

1. An a-c "hold-off" bias of 300 volts supplied by transformer $T1$.
2. An a-c "turn-on" bias of 220 volts supplied by grid transformer $T3$.
3. A peaked triggering voltage of approximately 200 volts peak from transformer $T2$.
4. A self-rectified d-c voltage across capacitors $C3$ and $C4$ which appears there as a result of grid current flowing during the time the grid was positive.

Normally transformer $T3$ is de-energized, rendering the firing tubes nonconducting by virtue of the negative grid bias throughout the period of positive plate voltage as shown in Figure 4*A*. Upon energizing grid transformer $T3$ (Figure 4*B*) the net a-c bias is reduced such that the peak of firing voltage from transformer $T2$ exceeds the critical grid voltage of the firing tubes, permitting them to be conductive and thereby initiating the power tubes. For accurate and synchronous timing, transformer $T3$ is energized from a thyratron timing circuit, but the time could be controlled by a simple pushbutton hand switch. The phase setting of the $T2$ firing peak is determined by a resistance-capacitor bridge in which the resistance element $R7$ is adjustable for changing the phase of the peaked firing voltage. The components in series with the primary winding of the peaking transformer $T2$ form a filter to insure only one positive firing peak each half cycle. This circuit is resonant so that voltage and current are approximately in phase. However, the peaked voltage of $T2S$ which is about 10 degrees wide occurs at current zero and is therefore 90 degrees out of phase with the phase-shifting voltage vector.

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The compensator may be adapted to any standard panel by three connections, 6, 7*B* (reconnection from 7), and 8 as shown in Figure 1.

Operation of the Compensator

The fundamental purpose of this compensator is to advance automatically the phase of the "peaker" firing voltages when the line voltage drops, and vice versa, to retard the phase should the line voltage increase. This is done by replacing the fixed transformer side of the resistance-capacitor phase-shift bridge with a voltage-dividing network which will vary in accordance with changes in line voltage. Referring to the elementary diagram of the compensator, Figure 5, the voltage divider consists of the primary winding of transformer *T*101 and resistor *R*101. Transformer *T*101 is made to act as a variable resistance by the action of the shorting tubes 102 and 103. The grid voltage of tubes 102 and 103 when varied causes the tubes to act as a variable resistance load in the secondary winding of transformer *T*101 and makes *T*101 appear substantially as a resistance in the voltage divider. The center point, 7*B*, of the voltage divider may be shifted back and forth by some magnitude e_s as shown in Figure 6. This causes a shift in the vector relation between vector 6–8 which corresponds to the phase of the line voltage, and vector 7*B*–9 which in turn determines the phase of the peaked firing voltage *T*2*S* of transformer *T*2 with respect to the line voltage. When the grids of tubes 102 and 103 are made less negative, tubes 102 and 103 appear as a lower resistance load and hence cause point 7*B* to move toward point 8, advancing the phase of the firing voltage vector *T*2*S* with relation to vector 6–8. In a reverse manner the phase of the firing peak may be retarded by making the grids of tubes 102 and 103 more negative.

To obtain the operating grid voltage, transformer *T*102 is connected directly across the line supply and its output voltage rectified by tube 101. By making time constants of the filter on the output of the rectifier voltage relatively low, this d-c voltage can be made to follow closely all fluctuations in the line supply. D-c output of the rectifier provides a reference voltage across the voltage regulating bridge (tubes 104 and 105), which at normal line condition give zero voltage across points 20 and 21. A d-c signal voltage directly proportional to the line-voltage change appears across these bridge output terminals.

It is necessary next to investigate the amount of compensation or phase shift required to maintain the welding current constant for a given line-voltage drop at various power factors of the welding circuit and per cent current settings. The higher the power factor, the greater will be the phase shift required; and likewise, the larger the percentage of full-phase current flowing, the greater will be the shift required to maintain the current. Figure 7 illustrates the approximate phase shift requirements to correct for a 10 per cent line-voltage drop for various power factors and per cent current settings. It should be apparent that once full-phase firing has been reached, no additional compensation can be obtained. Hence, if the line voltage falls to 90 per cent of its normal value, a maximum (depending on power factor) of approximately 95 per cent current can normally be delivered to the welding machine. The compensated timer requires a five per cent, and in some cases ten per cent, zero current gap to allow for high heat compensation by phase advance. It is, however, usual practice to include this slight zero current gap at full heat in most welding machines so that any changes in secondary power factor will not permit heat-control settings to range above 100 per cent sine wave current. Unstable operation might result in operating practice unless this slight open current gap was adjusted for the ordinary welder control panel.

Figure 8 shows how the setting of *P*101 is used to obtain a greater rate of compensation at higher than normal power factors. *P*101 is adjusted so that there is an unbalance as much as 20 per cent between the voltages 6–7*B* and 7*B*–8. When a voltage drop occurs, point 7*B* is moved toward 8 by the amount e_s. This produces an angular advance in the trigger firing voltage of a_1, a_2, and a_3 for high, intermediate, and low heat settings. For the range of 20 per cent to 60 per cent power factor, which covers most resistance welding setups, a_1 is substantially greater than a_2 and a_3 without too much unbalance between voltages 6–7*B* and 7*B*–8. Thus *P*101 is adjusted to obtain a curving characteristic of phase shift versus heat setting. *P*101 is used as a bridge sensitivity control and therefore acts to determine the slope of the characteristic curve. By correlating the two adjustments it is possible to obtain a compensator characteristic which closely approaches the requirements shown by Figure 7. That this has been accomplished is borne out by experimental results which follow.

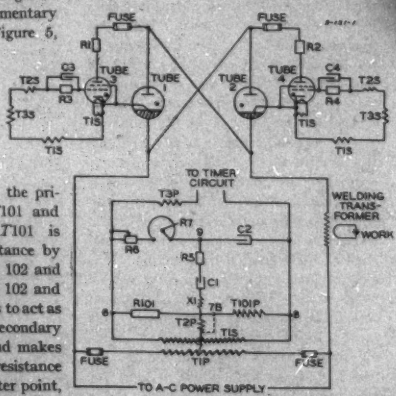


Figure 1. Simplified diagram of phase-controlled welding circuit

Figure 2. Panel with *PT* recorder and compensator installed

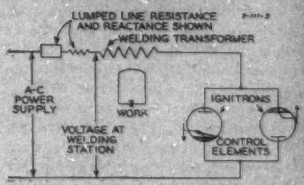
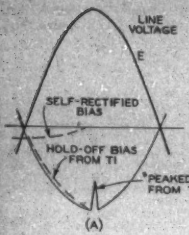


Figure 3. Typical welding power circuit

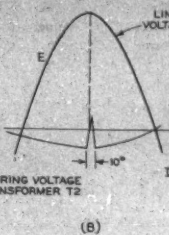
Data on Operating Performance

Referring to Figure 7, it is seen that the compensator must respond over a



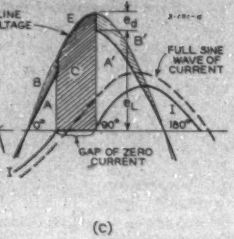
(A)

Figure 4A. One firing tube control voltage—standby



(B)

Figure 4B. Same firing tube voltage—for welding. Resultant grid firing voltage shown



(C)

Figure 4C. One half-cycle welding voltage and current showing instantaneous line drop

wide range of phase-angle advance for a variety of conditions that depend primarily on heat current setting and power factor. It must also be taken into account that the regulation may vary considerably, depending on the number of other machines that "hit" simultaneously. Differing portions may also be "chopped" off the useful area of the line-voltage wave as governed by the fractional heat dial settings of these machines. Then, too, interfering welders may also "come and go" early or late during a weld period. Fortunately, the control bridge circuit is very sensitive and responds correspondingly to all degrees of regulation, handling instantaneous line drops readily.

It would be well to consider briefly the instantaneous voltage drop imposed on a welding station by power transformer and feeder reactance. Standardization has not yet fully clarified the meaning of percentage voltage regulation for phase-controlled welding machines caused by this effect. From Figure 4C it should become apparent that with the form of voltage wave shape shown, the use of a voltmeter to register welding load voltage is inaccurate. The cathode-ray oscilloscope offers a better means of obtaining the voltage drop. The question then arises as to where to measure the voltage drop when speaking in terms of percentages. One criterion might be to consider the regulation as:

$$\% \text{ instantaneous regulation} = \frac{e_d}{e_L} \text{ at line-voltage peak (90 degrees)} \quad (1)$$

Here e_d and e_L are initial line drop and load voltage respectively. Also:

$$e_d = L\, di/dt \text{ for } i_a \quad (2)$$

where L = lumped power source inductance

In considering over-all welding regulation, it is necessary to discard the no-load voltage area C shown in Figure 4C. Regulation for the half cycle shown then becomes:

$$\% \text{ total regulation} = \frac{\text{area } B+B'}{A+A'+B+B'} \quad (3)$$

The voltmeter could measure this accurately for one condition, namely, full sine wave welding current, where an instantaneous drop does not normally occur. Strictly speaking, equations 1 and 3 must be reconsidered each time another fractional heat current is used. The reason for this is that partial heat currents are nonsinusoidal and have initial rates of rise that depend on the ignition point, that is, the controlled firing angle. The welding power factor also contributes to the degree of the instantaneous voltage drop. Thus the importance of instantaneous voltage drop cannot be overemphasized.

The detection circuit of the voltage compensator was designed to take into account this complication of measuring just such voltage regulation. The rectifier supply, which is in effect the detection circuit, has an inductive input filter which integrates the voltage wave, so that instantaneous drops that occur after 90 degrees will readily be averaged into the resultant output voltage.

A test was conducted using actual weld pull specimens and dropping the voltage by means of another timer operated simultaneously. The results with and without compensation are shown in Table I. Note that the average for 0.016-inch stainless steel with compensation is 399 pounds pull strength, whereas when uncompensated the average fell to 333 pounds strength because of external line drop. An ampere-squared second recorder indicated that approximately only 70 per cent heat was getting to the weld when uncompensated.[3] The difference is even more marked for 0.050-inch stainless steel, shown in Table II. Here the average fell from 2,634 pounds pull when compensated down to 2,063 pounds pull when not compensated for the particular line drop. The recorder indicated approximately 76 per cent heat into weld for the uncompensated case. A definite advantage in favor of the compensator was found as a result of these tests.

The compensator was next tested under severe conditions and operated with an instantaneous voltage drop as high as 27 per cent. Without compensation the recorder indicated that the heat into weld was about 50 per cent of normal. The compensator was therefore able to bring the heat up to 100 per cent (entirely back to normal). This is strikingly illustrated by shear strength pull tests which showed perfect weld strength of 2,300 pounds when compensated but fell off to 1,350 pounds when uncompensated for the drop referred to. Such a test points to suitable compensation for several heavy welders operating simultaneously, provided the power source is not being too severely overloaded. The main purpose of this test was to determine evenness of compensation under the wide variety of conditions mentioned earlier. With

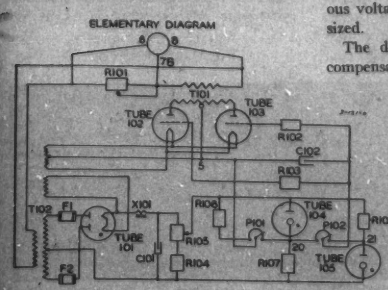


Figure 5 (left). Elementary diagram of compensator panel

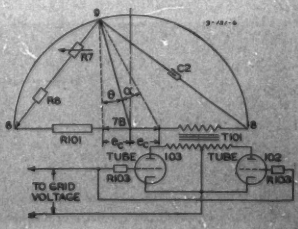


Figure 6 (right). Vector sketch showing how phase of peaked firing voltage is shifted by compensation

Heat control circuit is included. e_c is compensation voltage

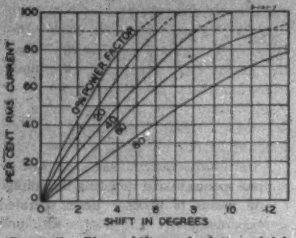


Figure 7. Phase shift required to maintain constant current with ten per cent line-voltage drop

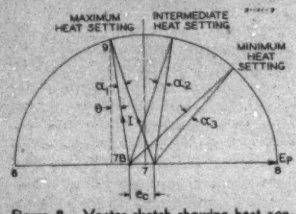


Figure 8. Vector sketch showing heat control range and point 7B shifted as required

various combinations of heavy and light loading for operation of both timers, deviations of the recorder for the most part hovered well within five per cent of normal. Adjustment of the compensator was not changed during this test. The greatest deviation experienced was over compensation of 15 per cent with the extremely heavy external drop referred to and then only for very low heat settings

Figure 9. Oscillogram of timer performance without compensation

A. Primary current of welding machine with installed compensator

B. Line voltage (240 volts a-c) common to both welding machines

C. Primary current of line-voltage dropping time

D. Voltage across *T*101 transformer primary winding in compensator. Adjusted value 260-volts a-c rms

E. Voltage across *R*101 bridge resistor in compensator. (Reduced in size for clarity.) Adjusted value 220 volts a-c rms

of the compensated timer. Even this is within tolerance limits and is remedied by reducing the power-factor-gain control slightly, if machine is operated continuously on this range. The power factor used was 0.6, which is fairly high, and the time was eight cycles. Consistent results were also obtained on lower power factors.

Oscillograms were taken to illustrate compensator action. In order to provide the line drop, a second timer known as a line dropping timer was operated on the same line. Referring to Figure 9, the two timers came on the line together, and the compensator-test timer had the compensator-gain-control knob *P*102 turned off. Thus, the test timer operated without compensation and when the dropping timer *C* stopped, the difference in the magnitude of weld current *A* is apparent.

Figure 10 illustrates normal compensation. The compensator acted fully on the weld current *A* within two cycles from the initial cycle dropping the line. After the external drop went off, the compensator required two cycles to phase back to normal, as seen by the amplitude of cycles 5 and 6 which are above normal. Since these oscillograms were taken, the speed of operation has been reduced to one cycle to yield full compensation. Notice the instantaneous drop expressed by the line voltage *B*. This same voltage drop (Ldi/dt) is experienced by every control transformer and circuit in the control panel and is seen by the dip of *T*101 (primary) voltage *D* of compensator and its related branch *R*101 shown as voltage *E* (reduced for clarity).

A better comparison is obtained from Figures 11 and 12. Figure 11 is without compensation and illustrates the current decrease from a normal rms value of 750 amperes, as read on the primary side of welding transformer. Figure 12 shows how this decrease was made up by compensation. Primary weld current *A* at cycle 2 became lower from an external load, but cycle 3 is almost up to normal compensation. Cycles 4 and 5 (and all further succeeding compensated cycles) appear normal. However, after release from the external load, cycles 6 and 7 continued to respond to phase advance. This is not particularly a disadvantage, as it tends to make up for the early partially compensated cycles (2 and 3). Cycles 8, 9, and 10 duplicate the initial cycle. It can be noticed that the shoulders, or phase concurrence for cycles 8, 9, and 10 are later than for compensated waves 3 to 7 inclusive. This accords with the principle of compensation employed. Were the oscillograph element *A* as responsive as element *C*, these shoulders would have the same flatness. Of importance, the peak amplitude of compensated current loops 4 and 5 need not equal normal loops 8, 9, and 10, since the criterion for equal compensation is that the rms value of the loop areas be equal in both cases. The instantaneous values of *D* and

Table I. Sample Shear Pull Strength Tests for Type 304 Stainless Steel 0.016 Inch Thick

Line Condition During Weld	I^2T Recorder in Per Cent of Normal Heat		Corresponding Weld Pull (Pounds)	
	With Compensator	Without	With Compensator	Without
Compensated weld machine. No line drop (start of test)	100 (Reference)	100 (Reference)	380	397
Compensated weld machine. No line drop (finish of test)	100 (Reference)	100 (Reference)	390	400
External line drop	95	71	418	332
External line drop	100	70	380	342
External line drop	100	70	400	328
External line drop	102	71	412	325
External line drop	100	72	385	340
External line drop	97	73	370	340
External line drop	100	71	375	322
External line drop	101	72	448	320
Average	99.3	71.3	398	332

Type 304 stainless steel 0.016 inch thick—1/4 hard

Weld time: four cycles. Weld current: 70 per cent (fractional). Electrode size: 1/4 inch. Electrode force: 340 pounds total. Line: 240 volts a-c. Regulation: six per cent. (Read with voltmeter during welding current, but using longer time.)

Regulation for instantaneous external line drop: 10 per cent. (Read with oscilloscope for partial current firing at approximately 100 degrees on voltage wave.)

Figure 10. Oscillogram of welding machine performance with compensation. Early line drop

See subcaption to Figure 9

Figure 11. Oscillogram of welding machine performance without compensation. Late line drop

See subcaption to Figure 9

E found in the oscillogram determine the shift of midpoint 7 of Figure 7. Voltage D corresponds to $T101$ voltage and E to $R101$, and their shift toward the right for compensation upward agrees with previous discussion. The I^2T recorder read 100 per cent normal heat for the oscillograms being compensated and dropped more than 15 per cent for those which were uncompensated, thereby causing lockout of the welding machine.

Although data were not taken for slow drifts in the sine wave value of line voltage, the response on seam welders using thermocouple ammeter indication has shown that the compensator handles such changes readily.

Investigating Compensator Performance

Several methods of investigating performance are available.

1. The cathode-ray oscilloscope, when connected to read one full cycle of weld current, will indicate the phase-angle advance during compensation. The oscilloscope is also helpful for making electronic control-panel power-factor heat adjustment after installing a compensator.

2. The I^2t recorder, illustrated in Figure 4, is well adapted to record changes in welding current. Where this recorder is available, a quick test is performed by operating two welding machines on the same line individually and together. Uniform recorder response, when the control panel is set to various heat positions, does indicate correct compensation where the regulation would otherwise drop the recorder below the 15 per cent heat limit and cause bad welding.

3. Spot-welding machines may be tested with either clamp-on pointer stop ammeter or pointer stop ammeters in conjunction with current transformers. The previous method for operating two welding machines together is recommended.

4. Seam welding machines may take advantage of a suitable ammeter such as a thermocouple type with an adjustable primary current transformer for indication of operation. Adjustment of the compensator is readily accomplished here, provided a definite line disturbance can be initiated during the test.

5. Where none of the aforementioned methods is available, the compensator can be adjusted and its operation checked by using merely a voltmeter across the control signal bridge and also across the primary winding of $T101$ for visually checking voltage swings. Normal adjustments once made need not be disturbed following one of these performance checks. The only special adjustments are

(a). The degree of compensation desired (same for all normal operation).

Table II. Sample Shear Pull Strength Tests for Type 304 Stainless Steel 0.050 Inch Thick

Line Condition During Weld	I^2T Recorder in Per Cent of Normal Heat		Corresponding Weld Pull (Pounds)	
	With Compensator	Without	With Compensator	Without
Compensated weld machine. No line drop (start of test)	100 (Reference)	100 (Reference)	2,700	2,800
Compensated weld machine. No line drop (finish of test)	100 (Reference)	100 (Reference)	2,600	3,100
External line drop	96	.82	2,725	2,200
External line drop	97	.83	2,725	2,400
External line drop	105	.70	2,600	1,900
External line drop	100	.75	2,625	2,000
External line drop	100	.73	2,500	1,800
External line drop	95	.73	2,600	1,800
External line drop	95	.72	2,700	1,850
External line drop	100	.76	2,750	2,100
Average	98.6	.75 .5	2,634	2,063

Type 304 stainless steel 0.050 inch thick—1/4 hard.

Weld time: nine cycles. Weld current: 75 per cent (fractional). Electrode size: 3/8 inch. Electrode force: 1,200 pounds total. Line: 240 volts a-c. Regulation: 10 per cent. (Read with voltmeter during welding current, but using longer time.)

Regulation for instantaneous external line drop: 15 per cent. (Read with oscilloscope for partial current firing at approximately 90 degrees on voltage wave.)

Figure 12. Oscillogram of welding machine performance with compensation. Late line drop

See subcaption to Figure 9

(b). A slight unbalance of voltages across bridge arms $R101$ and $T101$ to allow uniform response in installations where the welder power factor is much higher than normally experienced. All adjustments are quickly performed, using a combination voltage test set.

Conclusions

1. This voltage compensator helps to maintain uniform current for resistance welding despite the disturbing influence of other machines on the line feeder. With wartime urgency of using existing feeders and with limited use of copper, the problem of poor voltage regulation is eased considerably.

2. Instantaneous reactance line drops (chopped voltage waves) in the order of 30 per cent have been compensated for 100 per cent. Without compensation the heat output was otherwise 50 per cent of normal value.

3. Another feature is compensation for upward or downward line-voltage shifts during the working day.

4. The ability to make consistent welds on poorly regulated lines, is, of course, the chief advantage of the compensator. On installations where the weld recorder locks out the equipment when the value of I^2T swings out of the allowable range, the operator is forced to reset the welding machine and usually to make new weld tests and rewelds. The voltage compensator eliminates to a large degree the number of such lockouts caused by variations in current with a resulting saving in lost time.

5. The unit is inexpensive, simple, compact, easy to install and adjust. It is entirely automatic, since the response was designed for uniform compensation for any fractional heat current settings.

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2. Voltage Variation of Tolerance for A-C Resistance Welding, L. G. Levoy. *Welding Journal*, July 1942, pages 454–60.

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Thyratron Motor Control

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Synopsis: The control of d-c motors was one of the first electronic-control projects. Recent developments, particularly the fully automatic and co-ordinated control of the armature power circuit and the field power circuit, have greatly increased the acceptability of these controls for industrial use.

This paper describes the control functions associated with an all-electronic d-c motor drive, in which grid-controlled thyratron-tube rectifiers automatically perform the variable voltage functions associated with the d-c generator, exciter, and field rheostats of a conventional motor-generator drive.

In addition, the grid-control action of the thyratron-tube rectifier dispenses with the usual magnetic starting and accelerating control devices and gives superior motor performance in the matter of almost idealized constant-current acceleration and flat preset speed-control characteristics resulting from *IR*-drop compensation and regulated field excitation.

Reversing is accomplished by magnetic reversing switches which reverse the armature terminals relative to the rectifier. Contact duty during switching is minimized by the supplementary action of the thyratron tubes which themselves serve to interrupt and initiate the armature current. Proper grid-control sequence in these same tubes causes them to act as inverters during the decelerating portion of the reversing cycle so that the rotational energy of the armature is actually pumped back into the a-c system.

Stopping is normally by means of a dynamic braking resistor, although the motor may be decelerated to a stop by utilizing the inverter action associated with reversing to regenerate power back into the a-c system.

Similar control schemes are applicable to motor-generator-set drives to control the generator and the motor fields in response to co-ordinated signals of motor speed and loop currents.

THE basic problem of realizing the flexibility of a d-c motor where only a-c power is available can be readily solved by the use of thyratron-tube rectifiers. The source of direct current is obtained from the rectifier, and the grid-control feature offers a means of controlling the motor by low-energy grid circuits.

The control can make the motor perform in practically any way desired. The speed can be controlled in accordance with requirements of the machine it drives, such as holding tension in a wire-reeling machine or holding loops between the stands of a rubber, cloth, paper, or steel mill. The speed can be held constant over a wide range of load or line-voltage conditions. The torque output can be held substantially constant from zero to base speed. Protection during acceleration and on overload is possible by means of current limit built into the control.

The rating of the rectifier, the type of circuit used, and the rating of the individual power tubes determine the size of motor which can be so controlled. In the case of larger size motors, the output wave shape is more of a determining factor on the circuit used than the size of the motor. The rectifier circuits used conform to standard rectifier practice and will not be covered in detail in this paper. The conventional biphase half-wave circuit controlling a one-horsepower 230-volt d-c motor will be used as the example in describing the theory of operation. It will be noted that two rectifiers are required, one for the armature power and one for the field. When the motor is to be operated from base speed down, by varying the armature voltage, the field rectifier is uncontrolled. A variable-speed motor can be made to cover a wide speed range by using a controlled rectifier on the field as well as on the armature.

The armature rectifier consists of grid-controlled thyratrons, and the output voltage is varied by shifting the phase of the grid voltage of the thyratrons with respect to their anode voltage. There are several ways of shifting the grid voltage, but the one used in these controls is the conventional inductance–resistance bridge. The inductance will be the variable element by the use of a saturable reactor. In this way the output of the rectifier can be controlled by the small d-c current in the saturating winding of the saturable reactor. Such a circuit is shown in Figure 1.

Auxiliary D-C Control Power and Voltage Standards

Since direct current is required for these saturating windings, a source is provided by a small thermionic rectifier and anode supply as shown in Figure 2. The d-c voltage is filtered by means of a reactor *X*1 and capacitor *C*1 and fed through a current-limiting resistor *R*1 and the voltage-regulating tubes *A* and *B*.

Tube *B* is primarily used as a constant voltage reference against which various signal voltages are compared. It is an inherent characteristic of a glow tube that its terminal voltage will remain essentially constant at rated value even though the current through the tube changes widely. The tubes used in this circuit maintain approximately 75 volts, and it is by this means that a reference voltage for regulating purposes is established that will remain relatively constant irrespective of a-c line-voltage changes.

Tube *A* is connected in series with tube *B* to give a constant potential three-wire d-c system of 150/75 volts for the plate and grid voltages of the control tubes.

The d-c winding of a saturable reactor is connected in series with a triode vacuum tube *C*, and this combination is connected across the 75-volt d-c control bus furnished by regulator tube *A*. (See Figure 3A.) With a negative voltage on the grid of tube *C* there will not be any plate current, the reactor will be unsaturated, and the thyratrons are phased off. If the grid is made less negative, tube *C* will pass some current, and the reactor will be partially saturated, which will advance the phase of the grid voltage. As the grid voltage of tube *C* approaches zero, the reactor will be completely saturated, and the thyratrons will be full on.

Armature-Voltage Control

The control scheme consists of comparing a portion of the armature voltage with a preselected portion of the voltage-regulator tube's voltage. The difference between these two voltages is amplified and applied to the grid of the triode, which saturates the reactor controlling the grid phase shift on the thyratrons supplying the armature of the motor.

To couple the armature voltage to the triode which saturates the reactor, it is necessary to have a common point for the signal voltage from the armature and for the grid voltage applied to the triode. It is also necessary that the relation of these voltages be correct; that is, an increase in armature voltage above a preset voltage level should make the grid of tube *C* more negative so as to retard the phase of the thyratron grid voltage. By studying Figure 3B, it will be apparent

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that the voltage relations are incorrect and, if directly connected, would give incorrect operation. It is therefore necessary to change this relation.

This can be done as shown in Figure 3C as follows: The grid of tube C is connected to a voltage divider across the 150-volt control bus so that the grid is positive when tube D is passing very little or no current. Then, as more current is caused to flow through tube D, the grid of tube C will be pulled negative by the increased current through $R2$. It is now possible to control the phase of the thyratron grid voltage by changing the voltage on the grid of tube D with the relation correct for regulation of the armature voltage.

Armature-Speed-Control Potentiometer

With the cathode of tube D connected to the mid-point of a voltage divider across glow tube B, as shown in Figure 3C, the cathode will be $37\frac{1}{2}$ volts positive with respect to the negative bus. With zero voltage on the armature, the grid of tube D will be $37\frac{1}{2}$ volts negative, and the thyratrons will be in a condition to conduct full half cycles. As voltage on the armature builds up to nearly $37\frac{1}{2}$ volts, the thyratrons will shut off just enough to maintain a balance between the armature voltage and the $37\frac{1}{2}$-volt reference.

In order to permit the adjustment of the armature voltage or speed, resistor $R5$ is replaced with a potentiometer so that the cathode potential of tube D can be changed. In order to permit the use of 230 volts on the armature of the motor, a voltage divider is connected across the armature and a portion of the armature voltage compared to the reference voltage. This is shown in Figure 4. The potentiometer shown in the armature voltage divider gives a means of setting the base speed with the speed control set for maximum speed. This adjustment gives a means of compensating for commercial tolerances in resistors and tubes.

IR-Drop Compensation

Armature speed is proportional to armature terminal voltage only when the armature is drawing no current and is spinning freely with the field excited. Under these conditions, the armature voltage is the counter electromotive force or generated voltage of the armature conductors. When current flows in the armature, as when the motor shaft is loaded, the counter electromotive force and hence the true speed is less than the terminal voltage by an amount equal to the voltage drop in the resistance of the armature conductors themselves. If a constant shaft speed is to be maintained irrespective of load, it is necessary to raise the terminal voltage progressively as the load current increases, by an amount equal to the armature-resistance voltage drop. To do this it is only necessary to introduce in the armature-control circuit a voltage proportional to the armature current in such a direction as to hold a higher armature voltage as the load on the motor increases.

Although it would be possible to build an amplifier system that would amplify the millivolt drop of a conventional shunt to such a point that it could be used, it offers serious difficulties. In order to get a more suitable voltage, a special current transformer is designed to operate in the

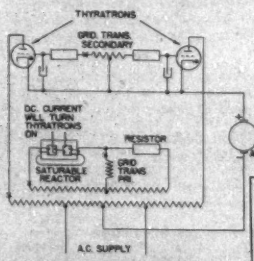


Figure 1. Grid-controlled rectifier with phase-shift bridge

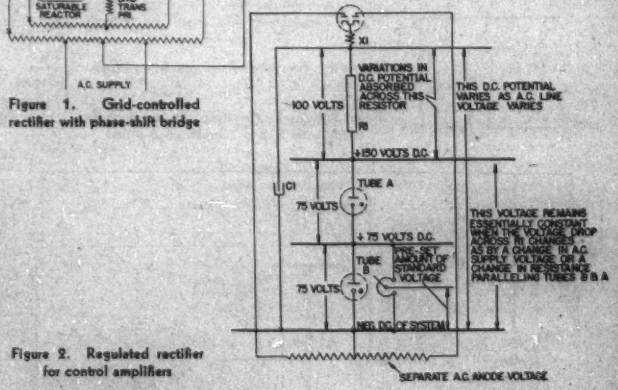

X1
VARIATIONS IN D.C. POTENTIAL ABSORBED ACROSS THIS RESISTOR
THIS D.C. POTENTIAL VARIES AS A.C. LINE VOLTAGE VARIES
100 VOLTS
R8
+150 VOLTS D.C.
C1
TUBE A
75 VOLTS
THIS VOLTAGE REMAINS ESSENTIALLY CONSTANT WHEN THE VOLTAGE DROP ACROSS R8 CHANGES AS BY A CHANGE IN A.C. SUPPLY VOLTAGE, OR A CHANGE IN RESISTANCE PARALLELING TUBES B & A
+75 VOLTS D.C.
TUBE B
KEEPS SUFF. AMOUNT OF STANDARD VOLTAGE
75 VOLTS
NEG. D.C. OF SYSTEM
SEPARATE A.C. ANODE VOLTAGE

Figure 2. Regulated rectifier for control amplifiers

anode leads of the rectifier tubes. The pulses of current through these anode leads are fed into the two primary windings so as to act as an alternating current that bears a direct relation to the direct current. The secondary winding of this current transformer is loaded by a resistor and a full-wave rectifier, and the resultant d-c voltage is directly proportional to the armature current. The value of this voltage for a given current can be adjusted with a potentiometer.

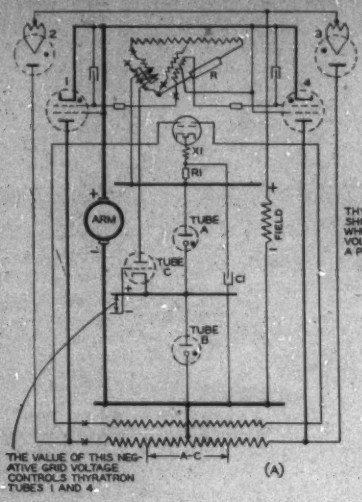
This d-c voltage that is proportional to armature current is connected in the lower end of the armature-voltage-divider circuit as shown in Figure 5. This added voltage in effect subtracts from that part of the armature voltage used as a feedback and therefore causes a higher voltage to be maintained by the regulating action. The adjustment provided permits setting the control for only partial compensation, or it can be overcompounded.

Figure 5A shows the effectiveness of the IR-drop compensation. The dotted curves represent the normal uncompensated motor-regulation characteristics. The solid curves were taken with the IR-drop compensation set for flat compounding at 100 per cent rated speed. Note the great improvement in the motor characteristics at the lower speeds.

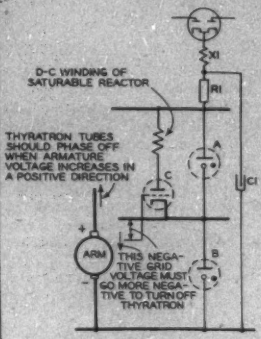
Current Limit

Current limit is necessary to prevent excessive currents being drawn during acceleration so as to protect the tubes and keep within the limits of commutation of the motor; otherwise, overloads could occur by suddenly applied shaft loads or by starting with a preset speed adjustment. A current-limit control should be inoperative from zero current up to the preselected value and then prevent the current rising above this value. If this were not the case, the current would be influencing the speed; instead, it should take over sharply as near the preset current value as possible.

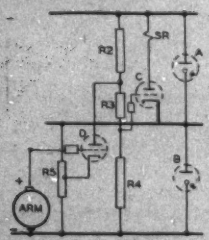
A d-c voltage proportional to armature current has been established for IR-drop compensation, and this same voltage can be used for current limit. A current-limit signal is established by comparing a portion of the d-c voltage that is proportional to current with a known voltage



A (left). Variable d-c source for saturable reactor


D-C WINDING OF SATURABLE REACTOR
THYRATRON TUBES SHOULD PHASE OFF WHEN ARMATURE VOLTAGE INCREASES IN A POSITIVE DIRECTION
ARM
THIS NEGATIVE GRID VOLTAGE MUST GO MORE NEGATIVE TO TURN OFF THYRATRON
(B)

B (above). Showing that armature voltage has incorrect sense to be coupled directly to grid of tube C

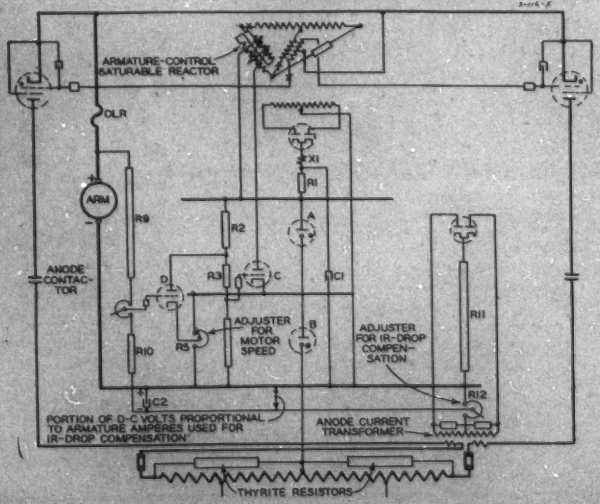


C (left). Showing that armature voltage now has correct sense to be coupled directly to tube D

If armature voltage tends to increase (becomes more positive), the grid of tube D becomes less negative and tube D turns on which turns tube C off which reduces saturation of SR which retards grid phase and reduces thyratron output

Figure 3. Armature-voltage-regulation circuit

Figure 5 (below). Armature-voltage-regulation circuit with IR-drop compensation added



standard and amplifying the difference by a triode. The circuit showing the connections for this control added to the armature control and *IR*-drop compensation is shown in Figure 6.

The value at which the current limit takes over is adjustable by means of the current-limit potentiometer. As long as the voltage on the slider is less than 75 volts, the current-limit tube *E* will be biased to cutoff, or practically so, and the armature-control tube *D* will have complete control. If high armature current causes the voltage on the current-limit-potentiometer slider to reach 75 volts, tube *E* will pass full anode current which will retard the grid voltage phase on the thyratrons. This reduces the current, and a balance will be reached. When the load on the motor is reduced and the armature current goes below the preset value, the armature-control tube *D* will take over and hold armature voltage as long as the current stays below the current-limit point.

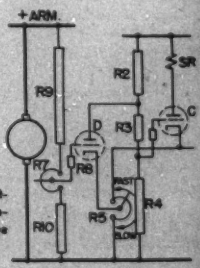


Figure 4. Armature-voltage-regulating circuit complete with armature-voltage divider

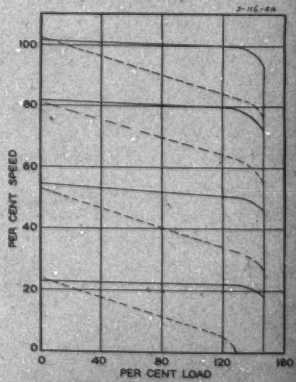


Figure 5A. Speed-regulation curves showing effect of IR-drop compensation

Dotted regulation curves are without *IR*-drop compensation. Solid regulation curves are with *IR*-drop compensation

With this type of control it is possible to accelerate from zero to full speed without drawing more than the preset value of current through the armature. During the operation of the motor, if excess load is applied, the speed will be maintained up to the point where the current reaches the current-limit setting. Beyond this point the preset value of current will be maintained in the armature even down to the stalled armature condition. The current will be maintained until the thermal overload relay functions.

When starting from rest with zero current or when reversing, there is no current to generate a current-limit voltage, and the armature voltage is zero; therefore, the first few half cycles of current might be of destructive magnitude. To overcome this objection, a normally closed interlock on the initiating contactor is used to give a false signal in the current-limit circuit. By means of a capacitor this false signal is "remembered" for a time after the circuit is closed and makes the current build up to the current-limit value rather than have one large surge of current and come down to the correct value.

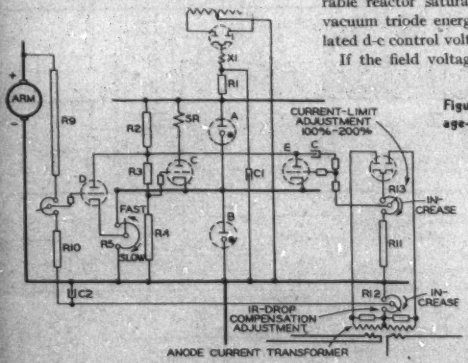


Figure 6. Armature-voltage-regulation circuit with current limit added

Figure 7 (below). Field rectifier with voltage control

Stopping

The rectifier characteristics of the thyratrons supplying direct current to the motor prevent the reversal of power from the motor to the a-c system when the motor is running faster than the speed called for by the control. This condition exists, for example, when the speed-control potentiometer is suddenly turned to a lower speed. In the case of high inertia loads this "electrical free-wheeling" characteristic is objectionable, but on friction loads it is of no consequence.

When power is removed for stopping, the same system of dynamic braking can be used as is found on magnetic control; that is, a resistor may be connected across the armature to absorb the stored energy. If quick slowdown is required, it is possible to add a control tube and a relay that will actuate the dynamic braking contactor to connect a resistor across the armature when the motor speed is above that called for by the control. When the speed is reduced to the called-for value, the tube initiates the function of disconnecting the resistor.

Field-Weakening Control

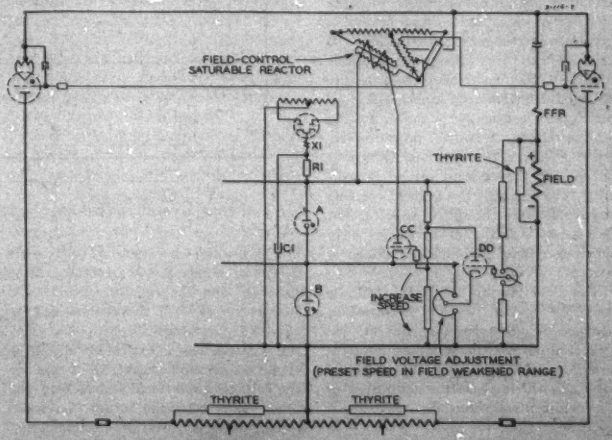
In order to expand the range of speed control, the shunt field rectifier tubes can be replaced with thyratrons and control added to the field. The control of the field rectifier is accomplished by using another saturable reactor and resistor bridge with the d-c winding of the saturable reactor saturated through a high vacuum triode energized from the regulated d-c control voltage.

If the field voltage is accepted as an indication of field flux, the control system can be similar to the armature-control circuit in that a voltage-regulating system is used. This regulating circuit is shown in Figure 7. The armature controls are not shown, to avoid confusion. The electric feedback of the field-voltage signal will maintain a preset level of field excitation independent of line-voltage variations.

Where the motor speed is being controlled by varying the armature voltage, the field excitation should remain at rated value to develop rated torque. Conversely, when operating the motor in the weak field range, the armature voltage should remain at rated value to develop constant horsepower. This characteristic can be had by ganging both the armature-control potentiometer and the field-control potentiometer on the same shaft. To do this each control is compressed into half the rotation, with the other half a conducting segment of negligible resistance. These are staggered so that with the armature-control slider in its active range the field-control slider will be on the conducting segment holding full field.

Speed Regulation at Reduced Field Excitation

When the field excitation is reduced the ratio between speed and armature counterelectromotive force is changed such that the armature must rotate at a higher speed in a weaker field in order to generate a given electromotive force. A given preset speed level is maintained relatively constant by grid phase control of the armature thyratrons as they phase



advance to compensate for *IR* drop accompanying changes in armature current.

In this system speed is not regulated by changes in field excitation. Speed is only preset to new levels by the field control but is regulated by armature control. When the armature voltage has been increased to the limit determined by the anode voltage, there can be no further regulatory action.

Field Excitation During Acceleration

It is necessary to apply full excitation to the motor field in order to accelerate it from standstill to base speed. Above base speed the field should be weakened slowly enough to keep the armature current within the commutating ability of the motor. Therefore, the application of armature voltage and the weakening of the field must be controlled by the current-limit circuit. By doing this, the motor is made to accelerate at the maximum possible rate permissible without drawing excessive current. Full field during acceleration from zero to base speed is maintained regardless of the setting of the field-voltage control.

The circuit that accomplishes the aforementioned features is shown in Figure 8. It is similar to the current-limit control on the armature voltage shown in Figure 6 in that the d-c voltage proportional to armature current is compared with a standard voltage, and the difference voltage is applied to a triode. The triode acts on the saturating circuit of the grid phase shifting reactor of the field rectifier.

There are two differences between the armature and the field control. First, an increase in armature current beyond a predetermined amount must increase the field strength by saturating the saturable reactor. When controlling the armature voltage, an increase in armature current necessitates a decrease in the saturation of the armature-control saturable reactor. Second, the standard voltage is not directly the constant voltage of regulator tube *B* but is the slightly variable voltage between the grid of tube *CC* and the negative bus, which voltage is in turn referred to the standard voltage of tube *B*.

The field forcing triode tube *EE* is connected so that, when it is caused to conduct by high armature current, the grid of tube *CC* will be pulled positive. The increased current in the anode of tube *CC* will increase the saturation of the field-control saturable reactor and apply more field.

Figure 8. Voltage-regulated field control with armature-current limit added

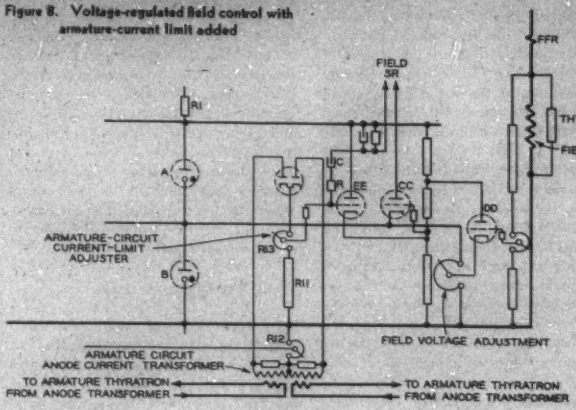


Figure 9. Armature-current-limit control connected to both the armature-voltage and field-voltage control

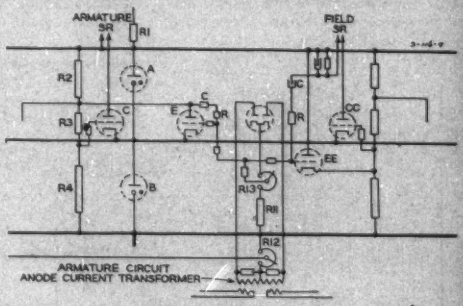
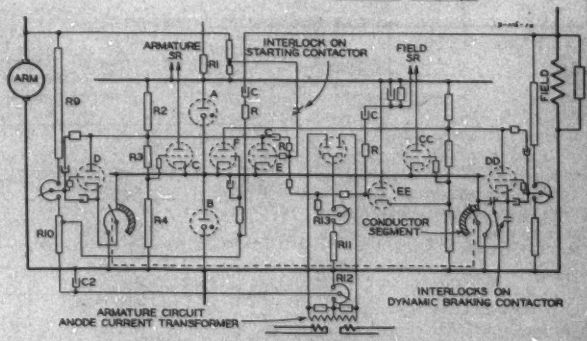


Figure 10 (below) Complete armature- and field-voltage controls



The normal operation of the circuit shown in Figure 8 will put the grid of tube *CC* and the cathode of tube *EE* slightly negative of the neutral bus, or almost 75 volts positive with respect to the negative bus. The grid of tube *EE* is connected to the negative bus except for the voltage proportional to armature current. This condition means that field forcing tube *EE* will be nonconducting until the armature current reaches a preset value determined by the setting of *R*13. Therefore, with the armature current below this preset value, the field regulator will operate normally, but tube *EE* will take over and increase the field as soon as the armature current exceeds the preset value.

The field forcing triode tube *EE* will act ahead of the armature current-limit

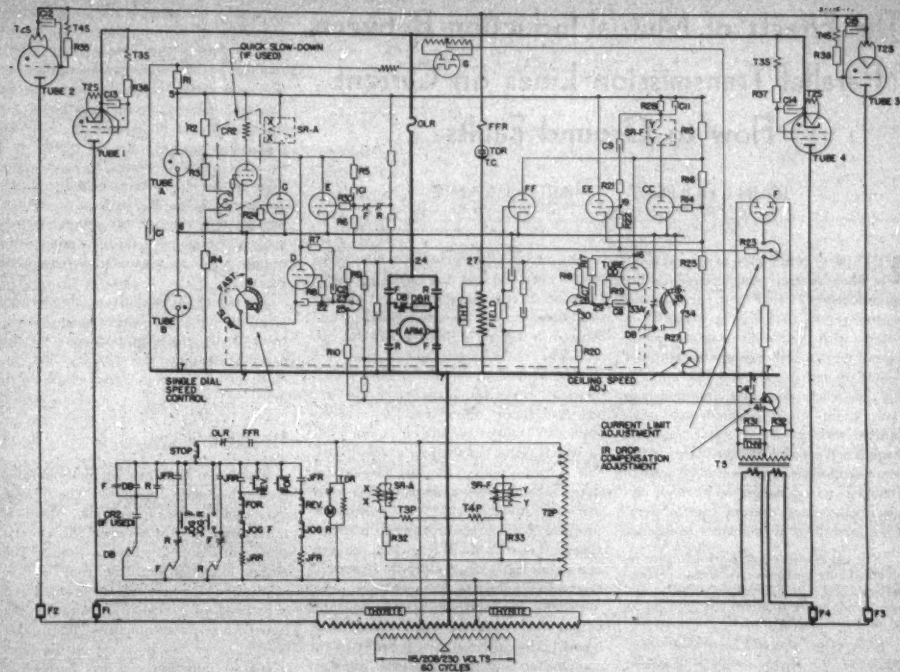


Figure 11. Complete power and control circuits of an electronic drive for a one-horsepower 230-volt d-c shunt motor

triode because the reference voltage of tube *EE* is slightly less than tube *E*. This is diagrammed in Figure 9 where both the field forcing and armature voltage control are shown connected to the same current-limit signal voltage. In the case of suddenly applied loads that do not give time for the field flux to build up to the needed value, the armature voltage will be reduced and prevent overloading the armature supply tubes. The two controls work independently and are arranged so that the field control works at a slightly lower value than the armature control.

The field circuit may be preconditioned to full field value prior to starting by means of interlocks on, say, the dynamic braking contactor. Then, when the starting is initiated, the false signal is removed, but its effect dies off more gradually because of capacitor discharge circuits and maintains full field until the armature current can take control via tube *EE*.

Armature-Voltage Limit When Decelerating

If the speed-control potentiometers are suddenly turned from the weak field condition to a speed calling for full field, the armature voltage will rise above the applied voltage. The voltage will rise because the full field would be applied suddenly and the motor becomes a generator. Because of the rectifying action of the thyratrons, current cannot flow from the machine into the line and dynamically brake the motor as it would be if connected directly to a d-c generator. This would be an objectionable condition, as it would endanger the insulation of the commutator and associated equipment.

This high generated voltage can be avoided by taking a signal from the armature voltage and actuating a triode that will retard the application of field when the voltage exceeds a preset amount. This preset value can be well above the operating value so that it will not interfere with normal control. This control is accomplished by tube *F* of Figure 10.

On nonreversing controls where the armature circuit is interrupted by an anode contactor instead of contacts at the armature terminals this armature-voltage-limit feature allows the use of a lower value of dynamic braking resistor than would normally be used on a motor being stopped from a weak field condition. The delayed field strengthening prevents excessively high armature currents when dynamic braking to rest by limiting the voltage across the armature.

Reversing Control

When the armature circuit is reversed by magnetic contactors between the output of the thyratrons and armature terminals, the duty on the contacts is much less than when the motor is supplied from a d-c generator. The duty on the contacts is reduced because the action of the thyratrons assists in interrupting the armature current. Because of the combination of inverter action and armature-current-limit control, the reversing cycle is such as to cause a uniform and rapid deceleration to zero speed, followed by acceleration to the preset speed in the reverse direction. During deceleration to zero speed, the rotational energy of the armature and the load is pumped back into the a-c system with the armature thyratrons. The preset speed in

The Effects of Mutual Induction Between Parallel Transmission Lines on Current Flow to Ground Faults

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THIS paper is intended to present some of the problems encountered in determining unbalanced fault currents and unusual results that may be expected on systems with parallel lines on a common right of way. Correct results are required so that proper co-ordination and application of relays may be accomplished. Fault studies must be made and constantly revised, as a power system changes and expansions take place. Also, future conditions must be studied so that intelligent selection may be made of circuit breakers and current transformers. It is the purpose of this paper to discuss

1. The use of the a-c network analyzer in solving fault problems by using certain mathematical simplifications which are necessary in order to adapt the problem to the analyzer's limitations.

2. Some rather unusual conditions which may occur on a system during fault conditions because of the effect of mutual induction between parallel lines.

Frequently two or more power transmission lines are built on the same right of way parallel to each other for partial distances or for the full length. The problem of mutual induction between such circuits arises when unbalanced faults occur on one line causing induced voltages in the parallel circuit. Where the lines are of the same voltage and bussed at either or both ends, the calculation resolves itself into the use of a simple equivalent circuit. The problem becomes more complicated when the lines are operated at different voltages which obviously cannot be bussed at one end, or when a fault calculation is required on one end of a pair of parallel lines whose opposite ends are unbussed, such as a split-bus arrangement. In solving a problem of the latter type, use is made of the a-c network analyzer which utilizes one-to-one ratio transformers to represent the mutual induction between lines.

Usually fault-current calculations are within the scope of a d-c calculating board. As a power system becomes more complicated and more than one line occupies the same right of way, in some cases operating at different voltages, the effect of mutual induction between the lines becomes important for unbalanced faults. A d-c board cannot be used for these more complicated conditions.

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Zero-Sequence Currents

Since the flow of zero-sequence current is not restricted to the physical conductor but must return through the ground circuit, the resistivity of the ground itself enters into the determination of its impedance. The effect of the ground return circuit upon the impedance can be determined by either one of two ways; namely, by direct measurement after the line is constructed, or by assuming an average value of ground resistivity for calculating the impedance by formula. The latter method is the one which must be used in most cases (see appendix). It is not deemed within the scope of this paper to discuss the various theories of current flow through the ground but to show how assumed conditions are used to obtain what are considered reasonable results.

The effect of mutual coupling or the resultant induction between parallel circuits is inversely proportional to the spacing between the circuits and directly proportional to the length of parallel.

Mutual Induction

When two transmission lines parallel each other close enough for the mutual induction to be appreciable, there is transformer action between the circuits when unbalanced currents flow. The mutual induction resulting from the flow of positive-sequence current is small and is reduced to a negligible value by the transposition of conductors. Transposition, however, has no effect on the zero-sequence induction. When paralleling two identical circuits of the positive-sequence network, the resulting impedance is one half of the impedance of one line. This is not true for the zero-sequence network for the reason that the flow of unbalanced currents will cause a certain amount of induction or mutual coupling to exist between the circuits resulting in a value somewhat greater than half the impedance for two identical circuits in parallel. The mutual impedance between the circuits tends to reduce the fault current under certain conditions and increase it under other conditions, de-

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each direction can be independently controlled by connecting different control potentiometers with interlocks on the reversing contactors.

Application to Motor-Generator-Set Drives

For those who have immediate need for this type of control characteristic for motors of, say 50- to 400-horsepower ratings, or even 2,000-horsepower, for that matter, it is practical to modify this equipment so that the thyratron functions associated with variable armature excitation of a one-horsepower motor would, instead, provide field excitation for the generator of a motor generator set, and the thyratron circuit for the field of the one-horsepower motor would be adapted to supply variable field excitation to the field of the larger motor. The loop-current control becomes more complex, particularly since d-c current must be measured directly and its direction of flow ascertained so as to give correct sequence of excitation to the respective fields of generator and motor during acceleration and deceleration. The reversing problem, too, is more complicated because of the necessity of reversing generator field excitation, but all this has been done.

Meanwhile, developments are progressing toward the use of ignitron-type tubes to provide armature excitation for motors of higher horsepower ratings than can now be supplied with the available hot-cathode thyratron tubes.

pending upon the relative directions of the ground current and the induced current. When a single-phase-to-ground fault occurs on an energized line, the resulting zero-sequence currents flowing through all three conductors in the same direction induce a voltage in the coupled circuit tending to cause an induced current to flow in the opposite direction to the one causing it. This may add to or subtract from the existing zero-sequence currents flowing in the coupled circuit to the fault through physical circuit ties.

Under certain conditions the amount of induction may be great enough to reverse the current flow in the coupled circuit when large fault currents flow. It may even change the direction of flow in nearby transformer neutrals, causing the current to flow in reverse of the conventional direction.

Devices for Representing Effect of Mutual Induction

Two lines having mutual induction between them may be represented by an equivalent circuit, provided the lines are bussed at one end. This presupposes that they are operated at the same voltage. The equivalent impedance is determined by subtracting the mutual impedance from the zero-sequence impedance of each line and adding it as a common impedance permitting solution by a reduction of circuits through arithmetical means. See Figure 1A.

This equivalent circuit may be used on an analyzer, but the solution is limited in its scope to lines of the same voltage bussed at one end. A device providing a more general and flexible arrangement is used on the network analyzer with alternating current applied to the analyzer. A transformer with one-to-one ratio is used, shunting an impedance equal to the mutual impedance across one set of terminals such that a voltage drop proportional to the mutual induction is reflected to the coupled circuit, inducing a current in the opposite direction to the originating current. This device may be used for lines of differing voltages and for unbussed lines. The analyzer setup is the same as for the equivalent circuit, and therefore requires that the mutual impedance be subtracted from the zero-sequence impedance of each line and that one side of the transformer be shunted with an impedance equal to the mutual impedance. Either side of the transformer may be shunted by the mutual impedance.

Modern systems may have some rather complicated conditions involving mutual impedance resulting from the construc-

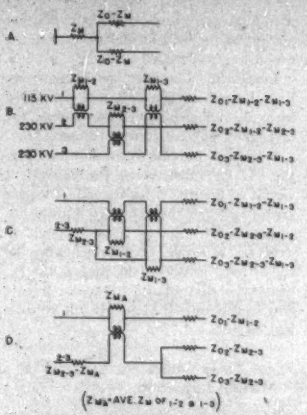

Figure 1A. Equivalent zero-sequence impedance circuit of two parallel lines (same voltage) for calculation of ground-fault current

Figure 1B. Use of one-to-one ratio transformers for representing the mutual induction between parallel lines on the a-c calculating board

Figure 1C. Simplification of the circuits in Figure 1B to reduce the number of one-to-one transformers required for the setup on the calculating board

Figure 1D. Further simplification of Figure 1B. This is only an approximation and is not accurate for all applications

tion of several lines on the same right of way, and their operation at different voltages. In solving problems of this type, resort must be made to simplification of circuits because the usual a-c network analyzer has few transformers for representing mutual induction. Where a number of mutual reactances are to be considered, as many simplifications as possible are made to represent the impedances between busses, and expansions are made successively by sections throughout the system as a detailed study is made.

Figure 2 shows a section of a possible system between stations *A*, *B*, and *C* with its several parallels. Figure 3 shows how the section was reduced to an approximate equivalent circuit requiring only two instead of six mutual transformers. Negative values of resistance and reactance may be encountered. The resistance component must be omitted. The reactance component may be handled in one of several ways. Where possible, the negative values of reactance may be combined with the positive values such as would be the case with the primary cir-

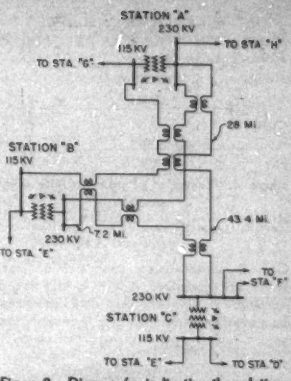

Figure 2. Diagram for indicating the relationships of mutual induction between the parallel lines connecting stations *A*, *B*, and *C*

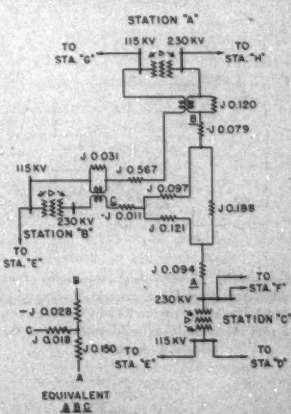

Figure 3. Simplification of the calculating-board circuits representing the lines connecting stations *A*, *B*, and *C* for calculating faults external to this section of the power system

Reactance values are on a per unit 50-megavolt-ampere base

cuit of the station *B* transformer bank in Figure 3, losing the identity of the station *B* 230-kv bus. Where this cannot be done, a capacitive reactance may be substituted for the negative value of inductive reactance on an a-c analyzer. The diagram in Figure 3 could be further reduced to save reactor units on the analyzer by using a delta-star transformation of the lines, but the net result still shows a negative value of reactance. Negative reactance values can sometimes be avoided if the mutual transformers have a ratio equal to the line voltage ratio. This simplified network would be

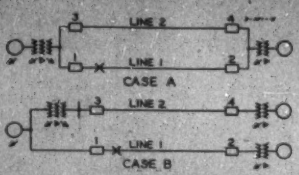

Figure 4. Examples of possible false relay operation

Case A represents two 230-kv lines operated temporarily at 115 kv

Case B represents the same pair of lines, with line 1 operated at 115 kv and line 2 operated at 230 kv, each line energized by a separate generator. The location of the ground fault in each case is marked by an *X*

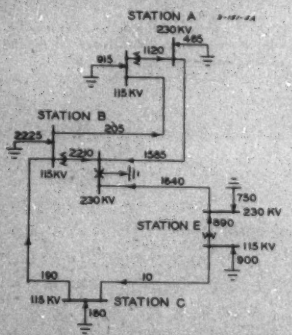

Figure 5A. Direction and magnitudes of the calculated ground-fault currents in amperes at 115 kv for a fault on the 230-kv bus of station *B* with the mutual reactances included for the calculating-board setup

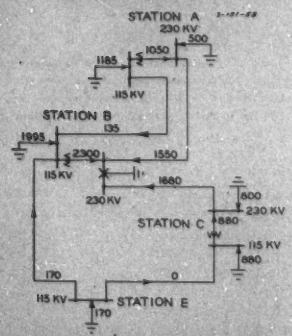

Figure 5B. Direction and magnitudes of the calculated ground-fault currents in amperes at 115 kv if the mutual reactances of the parallel lines are ignored in the calculating-board setup

Compare with current values shown in Figure 5A which include the effects of mutual induction

used during the study of faults in another section of the system and would require expansion for detailed study.

In reducing a network consisting of two lines bussed at one end and paralleled by a third line of different voltage, the arrangement is as shown in Figure 1B.

Figure 1B is reduced as shown in Figure 1C by substituting the equivalent circuit of Figure 1A for the lines that are bussed. When the values of mutual impedance are equal or close enough to average, a single transformer may be substituted as shown in Figure 1D because the sum of the induced currents flow in the mutual branch of the equivalent circuit.

False Relay Operation Because of Mutual Induction

Cases A and B, Figure 4, are two examples of how the effects of mutual induction could cause false relay operation if it is not considered in the relaying.

Case A

Case A represents two 230-kv lines operated temporarily at 115 kv. A power source is connected to each end of the circuit, and the two lines are bussed at both ends.

When the fault occurs as shown near the end of the line, a large current flows through breaker 1 resulting in quick tripping. At the same time, the induction-type current-polarized directional ground relay at 2 starts to operate. After breaker 1 opens, the direction of current flow in line 2 reverses, and, because of the extra induced current from mutual induction in the line, the directional overcurrent ground relay in position 3 may seal its contacts before breaker 2 opens, causing an unnecessary trip-out of the unfaulted line. Breaker 2 would probably have cleared before relay 3 closed its contacts if the added influence of mutual induction had not increased the current in line 2 to speed up the operation of relay 3.

Case B

Case B, Figure 4, represents the same pair of lines except that circuit 2 has been raised to 230 kv, and each line is energized by separate generators.

The fault is again placed at the same point on line 1, causing breaker 1 to open. This entirely isolates the two lines except for mutual induction between them which caused the unbalanced current to reverse in line 2 and therefore reverse the normal direction of the current flow in the transformer neutral. Relay 4, if current polarized, has both its polarizing and actuating current reversed so the resultant direction continues to be the same until breaker 2 opens. Relay 4 may close its contacts before breaker 2 opens, causing false relay operation of the circuit.

Effect of Mutual Induction on Ground Currents

Figures 5–7, inclusive, show diagrams with data obtained from a system fault study made on the a-c network analyzer and provide examples of the effect of mutual induction between circuits for ground faults. These examples are for the same section of the system as shown in Figure 2 except that the line from station *A* to station *C* is omitted. These

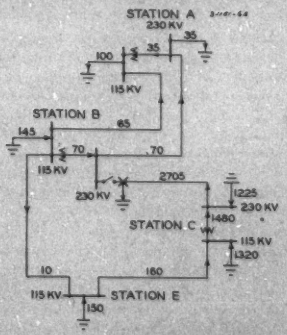

Figure 6A. Because of mutual induction between circuits it is possible to have appreciable ground currents flowing in sections isolated from the ground fault

Note current flow between stations *B* and *A*

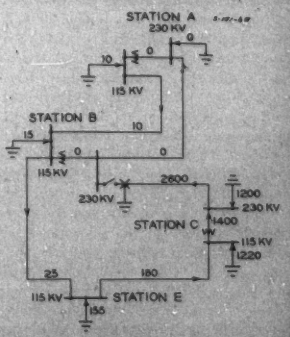

Figure 6B. The effect of ignoring mutual induction

Note negligible flow of ground currents between stations *A* and *B*

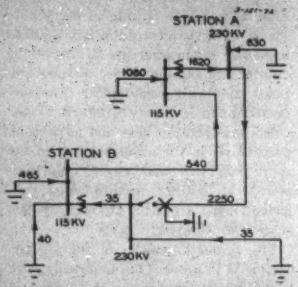

Figure 7A. The effect of mutual induction increases the over-all ground current flowing in parallel lines providing the currents flow in opposite directions

Note the effect on the station *A* to station *B* 115-kv line which parallels the 230-kv line for 35 miles. Compare with Figure 7B

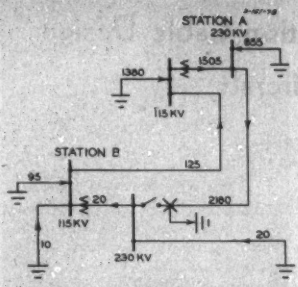

Figure 7B. Mutual induction is ignored in the calculations

The sum of the ground currents circulating in the 115-kv line and the station *B* 115-kv transformer neutral are equal to only 22 per cent of the calculated values of ground currents (shown in Figure 7A) when the mutual induction is included. In this case faulty relay operation could result if the effect of mutual induction is ignored

examples show faults on the end of transmission lines with values of ground current flowing before and after the adjacent breaker to the bus has opened for conditions with and without the consideration of mutual induction. All currents shown are equivalent amperes at 115 kv.

Figure 5 shows the effect of mutual induction between the 115-kv and 230-kv lines for a single-phase-to-ground fault on the station *B* 230-kv bus. When mutual induction is considered (Figure 5A), the calculated value of ground current in the 115-kv line is 205 amperes from station *B* to station *A*. However, when the effect of mutual induction is ignored (Figure 5B), the calculations show a flow of only 135 amperes in the 115-kv line, *but in the opposite direction to that shown in Figure 5A*. In this case the 115-kv line might be cleared by relay unnecessarily for a 230-kv line fault if one were not aware of the effect of mutual induction between paralleling lines of different voltages.

It is possible, as shown in Figure 6, to have appreciable ground currents flowing in sections isolated from the fault because of mutual induction between circuits. The effect shown in Figure 6 would be much more pronounced with longer parallels or larger concentrations of ground currents. Figure 6A shows the magnitude and direction of the ground currents circulating between stations *A* and *B* resulting from the effect of mutual induction when a fault occurs on a radial 230-kv line fed from station *C*. If mutual induction is ignored, results will be obtained similar to those shown in Figure 6B. In the latter case practically no current circulates in the lines between stations *A* and *B*.

The effect of mutual induction increases the over-all ground current flowing in parallel lines providing the currents flow in opposite directions. Figure 7 shows this effect very clearly on the station *A* to station *B* 115-kv line which parallels the 230-kv line for 35 miles. The mutual induction (Figure 7A) increases the ground current in the line and the station *B* transformer neutral practically fivefold over the values obtained in Figure 7B, which neglects mutual induction, for the same 230-kv ground fault. This is an instance that could very easily cause false relay operation, since erroneous results would be obtained by neglecting the mutual induction. Proper results could not be obtained on a d-c board since the lines are of different voltages.

Conclusions

A d-c calculating board cannot be used to represent the effects of mutual induction between lines operated at different voltages. The neglect of these effects may give erroneous answers serious enough to result in false relaying.

With two lines paralleling each other on the same right of way through which unbalanced fault current is flowing in the same direction, the effect of mutual induction between the lines is to reduce the flow of ground current.

The effect of mutual induction between two lines paralleling each other on the same right of way through which unbalanced current is flowing in opposite directions is to increase the flow of ground current.

It is possible, because of the effects of mutual induction between lines, to reverse the normal direction of the ground current flowing in the grounded neutral of a transformer bank to a ground fault.

Appendix. Formulas for Calculations of Zero-Sequence Impedances of Short Transmission Link Without Ground Wires

Zero-Sequence Impedance

$$Z_0 = R_c + 0.00477f + j.01397f \times \log_{10} \frac{D_e}{GMR \text{ circuit}}$$

(1) (Reference 1, page 157)

Z_0 = ohms per phase per mile

$$Z_m = 0.00477f + j.01397f \times \log_{10} \frac{D_e}{GMD \text{ circuit}}$$

(1) (Reference 1, page 158)

Z_m = ohms per phase per mile

f = frequency in cycles

D_e = 2,790 feet based on an average ground resistivity of 100 meter-ohms

(1) (Reference 1, pages 146–8)

$$GMR \text{ circuit} = \sqrt[n^2]{GMD \text{ sep}^n \times GMR \text{ conductor}}$$

(1) (Reference 1, page 157)

GMR conductor obtained from tables

(1) (Reference 1, page 138)

$$GMD \text{ sep} = \sqrt[n]{\text{three distances between conductors}}$$

R_c = resistance per mile of one conductor

$$GMD \text{ circuit} = \sqrt[n^2]{\text{nine distances between conductors}}$$

Conversion of ohms to per unit Z

$$\text{Per unit } Z = \frac{\text{base mva} \times \text{ohms}}{\text{kv}^2} \qquad (2)$$

For mutual impedance between lines of different voltages

$$\text{Per unit } Z = \frac{\text{base mva}^* \times \text{ohms}}{\text{kv}_1 \times \text{kv}_2}$$

References

1. Symmetrical Components (book). C. F. Wagner, R. D. Evans. McGraw-Hill Book Company, Inc., 1933.

2. Calculation of Short-Circuit Currents in A-C Networks. W. M. Hanna. *General Electric Review*, April 1937, pages 189–96.

* Megavolt-amperes.

High-Voltage-Ignition-Cable Design for Aircraft

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IN the design of an insulation, mechanical and chemical problems must be considered as well as the electrical problem. This is particularly true in the design of an ignition cable for aircraft.

Before constructing a suitable insulated wire or cable for any purpose, it is essential to know the conditions of usage. An aircraft ignition cable may be subjected to the following:

1. Abrasion and chafing.
2. Pulling.
3. Compression.
4. Vibration.
5. Heat.
6. Cold.
7. Moisture.
8. Oil and solvents.
9. Ozone.
10. Nitric acid.
11. Low pressures.

In addition, the insulation must have high dielectric strength and low capacitance.

The cable is subjected to abrasion, chafing, and pulling during assembly into the manifold and flexible conduit leads. This is emphasized by the close fitting manifold, made in an effort to save space and weight. Insufficient space is an enemy of insulation. Many engineers often neglect to allow enough space to prevent injury to insulations. It is appreciated that weight and space saving are very important, especially in aircraft, but proper functioning and safety should take precedence over space saving.

Compression of the cable takes place at the tightly fitting grommets within the spark plug and elbow fittings.

Vibration is quite severe while the engine is running.

According to aircraft-engine manufacturers, and engineers of the Air Services, the temperature in the spark-plug elbow may at times reach 325 to 350 degrees Fahrenheit. The temperature at the spark-plug gasket is 400 to 500 degrees Fahrenheit, and the spark-plug barrel or well may reach a temperature of 375 to 400 degrees Fahrenheit.

We are told that temperatures as low as −70 degrees Fahrenheit or even lower are encountered in high altitude flying and reach this at ground level in parts of the world where our planes are in operation. Although the cables are not flexed or moved at these temperatures, spark plugs may be changed at −20 degrees Fahrenheit or even lower. In such event the cable is flexed or bent to some extent.

Although the cable is entirely enclosed in shielding, moisture enters the system because of breathing, and condensation may take place. If moisture is absorbed by any part of the cable, arcing and premature failure may occur.

The cable comes in contact with lubricating oil and with solvents which are used to wash down and clean the engine.

The cable is exposed to the effects of corona. The ozone formed because of the high electrical stress on the air surrounding the cable is a powerful oxidizing agent. The effects of ozone on the cable can be observed internally next to the conductor as well as externally.

Ozone combines with nitrogen of the air to form oxides of nitrogen. These oxides form nitric acid in the presence of moisture. Nitric acid is also a very powerful oxidizing agent.

High-altitude flying has greatly complicated the problem of designing satisfactory aircraft ignition cables. Cables that function reasonably well at moderately low altitudes fail after relatively short service at very high altitudes.

So far as can be learned, the peak voltages impressed on the cables are in the magnitude of from 7.5 to 10.0 kv.

The dielectric constant of the insulation should be such that the capacitance of the cable will be low enough not to interfere with proper firing of the spark plug.

Consideration of the conditions of service makes it clear that designing a cable that will function satisfactorily is no easy problem. The conventional type of rubber-covered, braided, and lacquered cable is basically lacking in certain respects. The lacquer coating is deficient in resistance to abrasion and chafing. It is difficult, if not impossible, to moisture-proof the braid completely. The lacquered braid is readily attacked by the combined action of heat and nitric acid, particularly in the confined space in the spark-plug well and elbow. Furthermore, the lacquer coating when subjected to heat, especially at high altitudes, is seriously affected.

The primary purpose of the lacquer coating is to prevent ozone deterioration of the rubber compound. If the lacquer coating is ruptured, electrical failure is likely to result in a relatively short time.

It is apparent that there is a need for an improved cable, especially for high-altitude flying. The cable designer must therefore find more suitable insulating materials to produce a cable which will meet the requirements. It is also apparent that there must be a meeting of minds of the cable manufacturers, the harness manufacturers, the aircraft-engine manufacturers, and the engineers of the Air Services on certain compromises. It is unlikely that a cable can be made that will meet all the conditions enumerated previously to the extent desired by each individual engineer. One engineer may emphasize heat resistance, another cold resistance, or some other requirement. This emphasis on any specific property can only be met at the expense of some other equally important requirement. What we must arrive at is a balance of properties so that we will obtain a cable with the maximum of any one characteristic without undue reduction of any other necessary characteristics.

The present trend in specification writing is to emphasize performance tests rather than constructional details or requirements based on specific materials. Very often specifications which are not based on performance will prevent the development of improved products. This can occur when new materials become available which will meet conditions of service more satisfactorily but may fail to meet tests based on specific materials. Performance specifications on the other hand encourage development, use of new materials, and better design. It is more difficult to prepare performance specifications since the object is to simulate conditions of service with a reasonable margin of safety. However, when such specifications are finally achieved, it will usually procure a product more satisfactory for the intended purpose.

It is unusually difficult to determine the suitability of an aircraft-engine igni-

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tion cable. It is at best a long procedure to make power-plant tests, and heretofore laboratory tests have revealed comparatively little as to how the cable would perform in actual flight.

Ignition-cable manufacturers have had this under consideration for some time and have attempted to prepare performance specifications that would reproduce as closely as possible conditions actually encountered in service. One test method suggested for incorporation in a specification is termed "simulated flight test." Figure 1 shows this apparatus. It consists principally of a bell jar mounted on a base plate, with proper fittings for attachment of a spark-plug chamber, a spark plug and elbow assembly with a length of standard flexible conduit. A suitable heater coil is mounted around the elbow and spark plug. The bell jar is partially evacuated to the desired pressure. The sample of cable to be tested is assembled in the flexible conduit lead, and the assembly at the spark plug is made identical with that made on an actual engine installation.

These test conditions have been suggested and may be modified as more experience and data are obtained in testing with the apparatus:

Gasket temperature	500 ± 10 degrees Fahrenheit
Elbow temperature	325 ± 5 degrees Fahrenheit
Pressure in electrode chamber	20 ± 5 pounds
Absolute pressure in vacuum chamber	10 ± 0.5 centimeters mercury
Peak voltage	12.5 ± 0.5 kv
Added capacitance	250 micromicrofarad

An attempt has been made to simulate flight conditions by cycling as shown in the tabulation:

Time	Heat	Vacuum	Voltage
Start	On	On	On
¼ hour		Off	
1½ hours		On	
2 hours	Off		
2¼ hours		Off	
3 hours	On	On	On

The voltage is on continuously, and the schedule is continued a definite number of cycles or until failure occurs.

Figure 1. "Simulated flight test" apparatus with and without bell jar

The cycling is shown graphically in Figure 2.

This test method has been in use by cable manufacturers, and a great deal has been learned about faults and deficiencies of present types of cables. It has also been very useful in the testing of new designs.

Aircraft-Ignition-Cable Design

Conductor

The size of the conductor materially affects the capacitance of the cable, and its cross-sectional area should therefore be as small as possible, consistent with sufficient tensile strength for manufacturing and normal handling. The conductor commonly used for aircraft ignition cable is made with seven strands of 0.013-inch diameter corrosion resisting steel.

The conductor should be smooth, and the stranding should be concentric. This type of stranding most nearly approaches the form of a solid conductor. Any accentuated unevenness or roughness tends to concentrate the electric stress and promote puncture.

It has been found advantageous to use a "sealed" conductor in the construction of aircraft ignition cables to prevent air leakage through the conductor. Leakage occurs at high-altitude flying when the pressure in the spark-plug well is greater than that of the surrounding atmosphere. In case a sealing compound is used in the spark-plug well, it is apt to be forced into the cable along and through the interstices of the cabled conductor. The presence of air inside the cable will also result in the formation of ozone which may lead to internal failure.

The sealing of the conductor results in better adhesion between the conductor and the insulation, thus preventing the insulation from sliding on the conductor. A sealed conductor tends to reduce twisting or dislocation of the conductor which may be the cause of internal corona cracking because displacement of the conductor with respect to the insulation will permit air to enter the cable along the conductor. Twisting or dislocation places the insulation under stress. Stressed insulation is readily attacked by ozone, resulting in cracking and ultimate failure.

The sealing of the conductor is accomplished by extruding or coating the strand of wire used in the center of the cabled conductor with a suitable compound. When the other six strands are cabled around the coated wire, the compound is forced between the individual strands, completely sealing the conductor.

Insulation

If a sealed conductor is used, a properly designed rubber compound is satisfactory, since the effect of internal corona is eliminated. Rubber compounds have advantages in that the low temperature flexibility is excellent and electrical properties are good. The rubber stock pile is being rapidly reduced, and it may become necessary to find a substitute. Some of

Table I. Insulations

Material	Dielectric Strength	Resistance to Compression	Heat Aging	Ozone Resistance	Low Temperature Flexibility	Capacitance
Rubber	1	1	2	4	1	1
Buna S	1	1	1	4	2	1
Butyl rubber	1	2	1	2	3	1
Polyisobutylene	1	2	1	3	3	1

the synthetic rubbers appear to be suitable, and among those are the buna *S* and isobutylene types. Cables have been made with these substitutes, and tests indicate that they are quite satisfactory.

In Table I are listed materials which have been used or which are under investigation. It is assumed that the material is properly compounded for the application. The materials are rated in accordance with their comparative value as insulation for ignition cable. The lowest number indicates the greatest value.

Protective Covering

A lacquer coating applied over a braid is used to prevent deterioration of the insulation by ozone, oils, and solvents. It is lacking in resistance to abrasion and chafing. The lacquered braid does not have sufficient resistance to heat and nitric acid. It is, therefore, necessary to use a more suitable protective covering.

In Table II are shown some of the materials that have been investigated and applied as protective coverings for ignition cables. It is assumed that the material is properly compounded for the application. The materials are rated in accordance with their comparative value as protective covering. The lowest number indicates the greatest value.

Most of the failures of ignition cable on aircraft engines occur in the spark-plug well or spark-plug elbow. This is readily understandable, since the cable is subjected to intense ozone concentration at this point as well as nitric acid formed by the combination of ozone, nitrogen, and moisture. The temperature is also highest at this location. Heat combined with low pressure tend to cause blistering or swelling of the protective covering. With lacquered cable, blistering might occur on the first flight at very high altitudes. The condition can be readily reproduced in the "simulated flight test."

The disintegrated lacquer seems to contaminate the porcelain or other type of sleeving placed over the end of the cable as well as the insulating wall of the spark plug. This contamination may induce arc-over from the spring contact to the outside casing of the spark plug. The arc-over is most likely to occur at high altitudes, particularly if the Neoprene grommet does not completely seal the spark-plug well.

The most satisfactory material for a protective covering at present appears to be suitably compounded Neoprene. Neoprene sheaths are reasonably ozone resistant and are improved by incorporating into the compound antioxidants and waxy materials that tend to migrate to the surface. A coating of wax applied to the cable will also improve corona resistance.

Neoprene-sheathed cables have good low temperature flexibility and will withstand flexing at −40 degrees Fahrenheit. These cables should not be bent or flexed at lower temperatures. This resistance to low temperature is better than that of lacquered cables which should not be flexed at temperatures lower than −20 degrees Fahrenheit.

As previously stated, heat and low pressure existing at high altitudes tend to cause blistering or swelling of the Neoprene sheath at the spark-plug elbow. This exposes the insulation to the conditions in the spark-plug well and elbow.

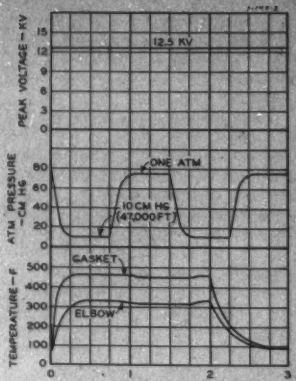

Figure 2. Graphs showing heat, atmospheric pressure, and voltage conditions during "simulated flight test"

Table II. Protective Coverings

Material	Resistance	Moisture Resistance	Heat Resistance	Ozone Resistance	Abrasion and Chafing Resistance	Low Temperature Flexibility
Buna *N'S*	2	1	1	3	1	1
Neoprene	2	1	1	2	1	1
Thiokol	1	1	3	1	1	1

It has been found that one factor causing blistering of Neoprene-sheathed cable is that the moisture absorbed by the cable in the steam vulcanization process tends to expand because of the temperature at the elbow. At low pressures the tendency to blister is greatly increased. The blistering caused by moisture can be prevented by preheating the Neoprene-sheathed cable for 24 hours at 180 degrees Fahrenheit.

Because of the limited space in the ignition-cable manifold and the increased surface friction of Neoprene-sheathed cables, there is greater mechanical abuse in wiring the harness than when lacquered cable is used. A glass-yarn braid applied between the primary insulation and the Neoprene sheath will impart added mechanical strength to the cable and help prevent stretching and twisting of the cable during manifold assembly. A glass-yarn braid also materially increases ozone resistance of the cable.

One disadvantage of a glass-yarn braid is the relative difficulty of sealing the cable when the pressure surrounding the spark plug and elbow is low as occurs at high altitudes. Air tends to flow through the interstices of the braid which may cause blistering or swelling of the Neoprene sheath at the elbow and lower the pressure in the spark-plug well. The spark-plug-well sealing compound may be forced up into the braid. This tendency of leakage through the braid can be partially overcome by applying a thin sheath of Neoprene over the insulation.

Table III. Relative Merit of Cables

	Braided With Lacquered Coating	Neoprene Sheath No Braid	Neoprene Sheath Glass-Yarn Braid Over Insulation	Neoprene Sheath Glass-Yarn Braid Between Layers of Neoprene
Abrasion and chafing	Poor	Excellent	Excellent	Excellent
Pulling	Fair	Poor	Excellent	Excellent
Compression	Poor	Fair	Fair	Fair
Heat	Fair	Good	Good	Good
Cold	Fair	Good	Good	Good
Moisture	Fair	Excellent	Good	Good
Oil	Excellent	Good	Good	Good
Aromatic solvents	Poor	Fair	Fair	Good
Ozone	Excellent	Good	Good	Excellent
Nitric acid	Poor	Excellent	Excellent	Excellent
Low pressure	Poor	Excellent	Fair	Good

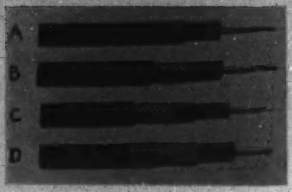

Figure 3. Four ignition-cable constructions

A. Sealed conductor, insulation, Neoprene sheath

B. Sealed conductor, insulation, glass-yarn braid, Neoprene sheath

C. Sealed conductor, insulation, Neoprene layer, glass-yarn braid, Neoprene sheath

D. Conductor, insulation, cotton yarn braid, lacquer coating

The glass-yarn braid is then applied, followed by a second sheath of Neoprene. The braid thus becomes thoroughly imbedded between the layers of Neoprene. This construction further increases the ozone resistance of the cable.

Figure 3 shows constructions which have been discussed. Figure 4 shows deterioration of lacquered-type cable at spark-plug elbow after being subjected to "simulated flight test" and after service on aircraft engine.

Use of Five-Millimeter Cable in Place of Seven-Millimeter Cable

In the wiring of the conventional type of manifold, the seven-millimeter cable receives considerable abuse. Undue pulling or twisting of the ignition cable in harness wiring may occur, resulting in very serious permanent injury to the insulation. Twisting of the cable is apt to produce air pockets along the conductor because of dislocation of the insulation with respect to the conductor. Excessive pulling on the cable may result

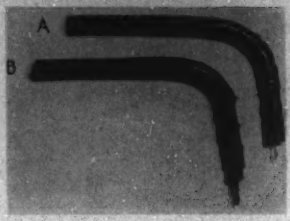

Figure 4. Samples of lacquered cable showing deterioration at spark-plug elbow

A. After "simulated flight test"

B. After service on aircraft engine

in elongation of the conductor and stressing of the insulation. The Neoprene-sheathed cable is more resistant to abrasion and chafing than braided and lacquered type, but nevertheless must be handled with reasonable care. Because of the limitations of space, it is doubtful whether seven-millimeter Neoprene-sheathed cable can be assembled in the present manifolds without injury to the cable. The use of five-millimeter cable in place of seven-millimeter cable would simplify the problems of harness assembly and remove the principal source of cable abuse.

Since the puncturing voltage of the five-millimeter Neoprene-sheathed cable is ample, and since cable failure is largely due to deficiencies in chemical and physical properties, it appears that this cable would be entirely satisfactory. The capacitance of an installation with five-millimeter cable is satisfactory since with present manifold and flexible conduit sizes and the same type of cable, the capacitance of the individual leads is less than when seven-millimeter cable is used because of the additional air space in the manifold. This favorable condition would only exist so long as the manifold size remains the same or is reduced only to a point that ample space is allowed to prevent mechanical injury to the insulation of the five-millimeter cable. Should the manifold size be reduced to fit the five-millimeter cable as closely as the present manifold fits the seven-millimeter cable, the same objectionable difficulties in assembly will exist.

Four types of cables have been under consideration. None of these cables meet all of the requirements to the extent desired. Any one is superior in some respects and deficient in other respects. It must be recognized that some of the requirements asked for by aircraft-engine manufacturers and engineers of the Air Services cannot be fully met. As an example, if it is essential to have a cable withstand the solvent action of highly aromatic gasolines, none of the cables under consideration would be entirely satisfactory. Again, if flexibility much below −40 degrees Fahrenheit is required, these cables would not be suitable.

In Table III, an attempt has been made to estimate the relative merits of the four cable constructions under consideration as to the conditions of usage on engine installations previously outlined.

Cable manufacturers at present are doing intensive development work in an effort to improve aircraft ignition cables. The numerous new materials which are being made available by the chemical industry are being thoroughly investigated, and advantage is being taken of those showing promise. Recent close cooperation between the engineers of the Air Services, the aircraft-engine manufacturers, and the cable manufacturers has greatly accelerated the development and improvement of ignition cables, and this will no doubt result in continued progress.

Dethermalizing Arc Quenchers

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Synopsis: The primary function of the normal-type oil circuit breaker is to interrupt the circuit as rapidly as possible, without disturbing the connected system, and to leave the oil circuit breaker in substantially the same electrical and mechanical condition as before. The interruption of an electrical circuit is always accompanied by an arc, and it has been found that if the arc and its associated space are rapidly cooled or dethermalized it is readily extinguished. This paper describes dethermalizing arc quenchers that cause the arc and its associated space to be cooled by the controlled flow of oil through and around the arc. The action of these quenchers has been verified by field tests on the 16-kv and 220-kv systems of The Southern California Edison Company Ltd.

IN the operation of large electric systems, effort is continuously exerted to gain reliability and at the same time to cut down maintenance costs. One of the costly maintenance problems is the overhauling of oil circuit breakers. It is the customary rule, based on experience, to overhaul oil circuit breakers after each short circuit or at least after two interruptions of short circuit. The overhaul periods of the oil circuit breakers could be greatly lengthened if the contact burning and the oil carbonization could be reduced. In order to accomplish these desired results it is important to cut down arcing time and contact separation during the arcing period.

Conclusion

The proper design of dethermalizing arc quenchers will interrupt short circuits of any magnitude without carbonizing the oil or changing its dielectric value, and because of the short arcing time the burning of the contacts becomes negligible.

Even though this short arcing time is accompanied by an extremely short contact separation, the continuously flowing oil prevents restriking of the arc. Consequently, with short arcing time and short arc lengths the arc energy is so greatly reduced that mechanical disturbances are eliminated.

The field tests on the Southern California Edison Company Ltd. system proved that the dethermalizers are adequate to interrupt short circuits ranging from a minimum to maximum duty without mechanical disturbance to the switch and without electrical disturbance to the system. The time of interruption decreased with the greater duty, thus giving the switch a larger factor of safety or an increased kilovolt-ampere rating.

Tests were made on the Edison system at widely separated locations, resulting in the same interrupting characteristics; that is, with the same kilovolt-ampere duty, the arcing time and contact separation were substantially the same, proving that the dethermalizers are adequate for all locations on the Edison system.

The record of operation of these dethermalizers during the past six or seven years has shown no deterioration of oil contacts, or insulating materials of the interrupters, and they have cleared all short circuits and line dropping incident to normal operation.

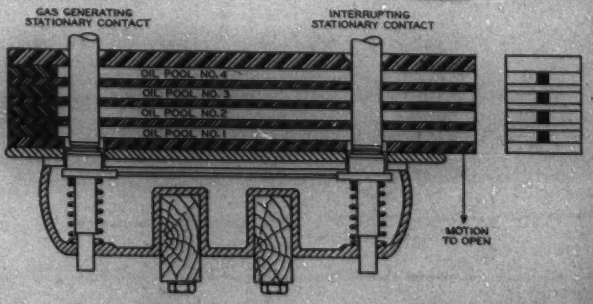
From this operating experience it becomes apparent that this type of arc quencher will result in the very minimum of maintenance and at the same time will give a maximum of system protection.

16-Kv Field Tests, August 25, 1936

Since the Edison company is practically the only company that uses 16 kv for distribution, it was desirable to have a breaker for this voltage with approximately 50,000-kva interrupting rating, small in size and fast in operation. Breakers of the normal type had insufficient interrupting capacity and required considerable maintenance. The dethermalizer for this breaker is shown in Figure 1. It can be seen from this sketch that the dethermalizing element has a multiplicity of pools of oil that are connected to restricted ports on one end, the other end is closed. The arc at the closed end generates gas which produces sufficient pressure to drive the oil in the pool, located between the contacts, through the arc and associated space of the other contact. As the contacts separate, other pools of oil are successively driven into the arc and the arc space of the second contact thus continually cooling the arc and the arc space until a point of extinction occurs, and sufficient cool oil is maintained through this space even after extinction so that restriking does not occur. This rapid cooling of the arc and its associated space is the dethermalizing action that extinguishes the arc.

Figure 2 illustrates a 16-kv 50,000-kva series-trip mechanical trip-free breaker set up for test. This breaker interrupted a 53,000-kva three-phase short circuit on a delta system feeding only the setup from a separate transformer bank. It operated on a close–open test in 3½ cycles total time. Figure 3 shows the oscillogram of this test. This switch was closed by hand on a three-phase short circuit and cleared with no disturbance. This test was repeated several times with the same results and when examined showed very little deterioration of contacts, oil, and dethermalizer. Breakers of this design have an operating record of six and one-half years, show no signs of oil carbonization, and have not required any maintenance.

Figure 1. 16-kv dethermalizer, flat-plate construction



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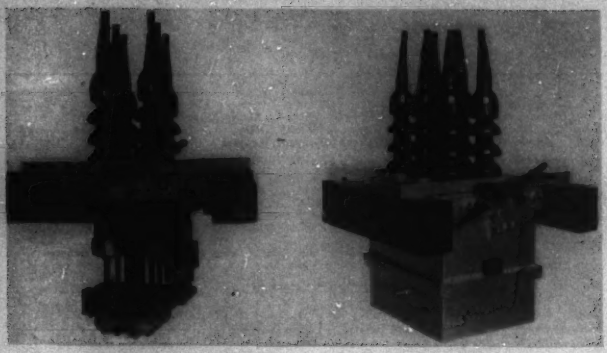

Figure 2. 16-kv oil circuit breaker with dethermalizers set up for field test

Figure 3. 16-kv close–open test, 53,000-kva three-phase short circuit

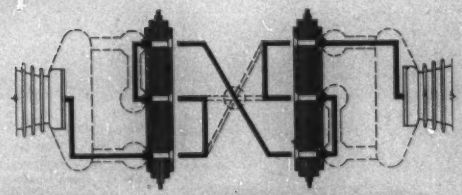

Figure 4. Arrangement of six-break dethermalizers

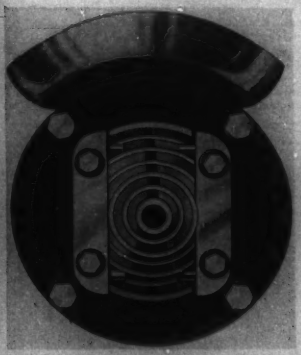

Figure 5. End view of 230-kv tube-type dethermalizer

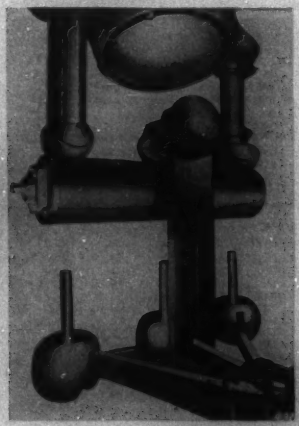

Figure 6 (right). Assembly of 230-kv dethermalizer on switch bushing

illustration clearly shows the shielding and one-half the crosshead.

Figure 7 shows the dethermalizer of the flat-type construction and the various oil pools or reservoirs. The end view shows the graded ports and the plan view shows the restriction of the ports.

When the switch contacts are parting, arcs are formed at each contact. The arc at the center contact will generate sufficient pressure to force the oil in the pools (located between the center contact and the outside contacts) through the outside arcs and through the ports at each end of the large tube. As the contacts are opening, new pools of oil are successively forced through the outside

230-Kv Dethermalizers

The dethermalizers for the 230-kv oil circuit breakers are made in the form of six breaks per pole or three breaks per bushing. The electric connections and sequence of these breaks are shown by Figure 4. The dethermalizers are made in the form of large tubes. Figure 5 shows the end view of the tube type. The graded ports can be seen in this figure. Each dethermalizer is mounted on the end of the switch bushing as shown by the assembly photograph, Figure 6. This

Figure 7. Type *H* dethermalizer flat-type construction, 230 kv

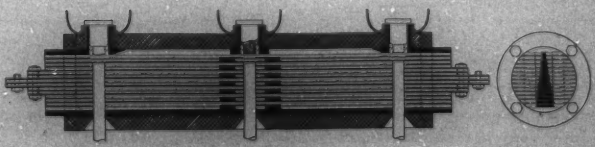

Table I. Tests Made at Saugus Substation, October 4, 1936

Kelman Dethermalizing Arc Quenchers, Type As Indicated

Test Number	Initial Voltage Phase to Phase (Kilovolts)	Type of Quencher Tube	Number of Breaks Per Phase	Phase Tank	Duty Cycle	Current Interrupted (Rms Amperes)	Equivalent Three-Phase Kilovolt-Amperes Interrupted	Closing Time (Cycles)	Over-all Time of Short Circuit (Cycles)	Relay Time (Cycles)	Breaker Interrupting Time (Cycles)	Contact Separation When Arc Extinguished (Inches)	Total Arc Length (Inches)
1	220	C	6	A	O	778	296,470		8.0	1.0	7.0	3 1/8	18 3/4
1A	220	C	6	A	CO	883	336,480	65	7.0	1.0	6.0	3	18
1C	220	*	6	C	O	787	299,897		6.5	1.0	5.5	2 1/4	13 1/2
1AC	220	*	6	C	CO	777	296,090	67	9.0	1.0	8.0	3 1/4	21
2	220	C	6	B	O	1,162	442,800		6.5	0.75	5.75	1 3/8	8 1/4
2A	220	C	6	B	CO	1,171	446,225	68	6.5	1.0	5.5	1 1/4	8 1/4
3	220	C	6	B	O	Not recorded because of oscillograph film choke. Same kilovolt amperes interrupted as test 3A							
3A	220	C	6	B	CO	2,055	783,090	69	7.0	0.75	6.25	1 3/8	9 3/4
4	220	C	6	B	O	4,142	1,578,363		5.5	0.75	4.75	1 3/8	6 3/4
4A	220	C	6	B	CO	4,526	1,730,000	69	5.5	1.0	4.5	1 1/4	6 3/4
4A1	220	C	6	B	CO	4,249	1,619,140	69	5.3	1.0	4.3	1	6

* In tests 1C and 1AC the dethermalizers were of the flat-plate construction, and the ports were not graded. All other tests were made with the type C dethermalizers which were of the round-tube construction with graded ports.

O—Open. CO—Close-open.

Table II. Tests Made at Laguna Bell Substation

Tests Made on July 10, 1938, on Kelman RA6J Breaker, 1,200 Amperes, 230 Kv, Serial Number 16408

Test Number	Initial Voltage Phase to Phase (Kilovolts)	Type of Quencher Tube	Number of Breaks Per Phase	Tank	Duty Cycle	Current Interrupted (Rms Amperes)	Equivalent Three-Phase Kilovolt-Amperes Interrupted	Over-all Time of Short Circuit (Cycles)	Relay Time (Cycles)	Breaker Interrupting Time (Cycles)	Breaker Dead Time (Cycles)	Arcing Time (Cycles)	Contact Separation When Arc Extinguished (Inches)	Total Arc Length (Inches)
Test Made on July 10, 1938, Original Installation, 1 1/8-Inch Bayonets and 1 1/2-Inch Clearance Holes														
1	210	A	6	West	O	660	240,000	25.0	0.36	24.64	2.60	22.04	17 9/16	104 1/8
1A	210	A	6	West	CO	630	230,000	12.2	0.48	11.72	3.94	7.78	5 1/16	31 1/8
1B	210	A	6	West	O	660	240,000	12.0	0.39	11.61	2.80	8.81	5 1/16	33
1AA	210	A	6	West	CO	660†	240,000	24.5	0.43	24.07	3.90	20.17	17 1/16	105
Note: Larger values of short-circuit current were not imposed because of the excessive arc length.														
Test Made on July 31, 1938														
1-C	210	C	6	East	O	No record obtained								
1-C	210	C	6	East	O	576	210,000	8.10	0.37	7.73	3.26	4.47	2 1/16	14 1/8
1-G	210	G	6	West	O	576	210,000	8.02	0.40	7.62	2.75	4.87	2 9/16	15 3/4
1-H	210	H	6	Middle	O	573	209,000	7.97	0.36	7.61	2.71	4.90	2 3/4	16 1/2
1A-C	210	C	6	East	CO	570	207,000	10.3	0.34	9.95	4.11	5.85	3 3/16	21 1/4
1A-G	210	G	6	West	CO	576	210,000	10.47	0.33	10.14	4.03	6.11	3 1/16	23 1/4
1A-H	210	H	6	Middle	CO	576	210,000	8.92	0.31	8.61	4.21	4.4	2 3/16	15 3/4
2-C	210	C	6	East	O	1,517	551,000	6.54	0.26	6.28	2.79	3.49	1 3/4	10 1/2
2-G	210	G	6	West	O	1,529	557,000	6.55	0.37	6.18	3.09	3.09	1 1/16	9
2-H	210	H	6	Middle	O	1,520	553,000	6.02	0.30	5.72	2.72	3.00	1 3/16	8 1/2
2A-C	210	C	6	East	CO	1,529	556,000	7.00	0.29	6.80	4.08	2.72	1 3/16	9 3/4
2A-G	210	G	6	West	CO	1,525	555,000	8.00	0.34	7.66	4.14	3.52	2 1/16	12
2A-H	210	H	6	Middle	CO	1,517	552,000	7.68	0.36	7.32	4.06	3.26	1 15/16	11 1/4
3-C	210	C	6	East	O	2,720	990,000	6.55	0.31	6.24	2.98	3.26	1 3/16	9 3/4
3-G	210	G	6	West	O	2,780	1,011,000	6.05	0.28	5.77	3.01	2.76	1 1/16	8 1/4
3-H	210	H	6	Middle	O	2,750	1,000,000	5.04	0.46	4.58	2.79	1.79	11/16	4 1/2
3A-C	210	C	6	East	CO	2,659	967,000	6.59	0.40	6.19	4.17	2.02	1 1/16	7 1/2
3A-G	210	G	6	West	CO	2,639	960,000	7.20	0.38	6.82	4.02	2.80	1 5/16	10 1/2
3A-H	210	H	6	Middle	CO	2,610	950,000	6.63	0.30	6.33	4.03	2.30	1 3/16	8 1/4
4-G	210	G	6	West	O	No record obtained								
4A-G	210	G	6	West	CO	4,720	1,719,000	6.06	0.35	5.71	3.89	1.82	1	6
4A-H	210	H	6	Middle	CO	5,075	1,850,000	5.97	0.30	5.67	4.05	1.62	1	6
5-H*	210	H	6	Middle	O	6,200	2,259,000	5.48	0.25	5.23	3.26	1.97	3/4	4 1/2
5A-H*	210	H	6	Middle	CO	6,070	2,100,000	6.06	0.30	5.76	4.20	1.56	7/8	5 1/4

* See oscillograms in Figures 11 and 12.

Types of quencher tubes: Type C—Round-tube type as tested at Saugus 10-4-36. 1.050-inch bayonets, center clearance-hole 1 3/16 inch and clearance-holes round-end, 1 1/16 inch x 1 1/16 inch.

Type G—Flat-plate style, designed to have the characteristics of type C, as nearly as practical. 1-inch bayonets, clearance-holes 1 1/16 inches.

Type H—Flat-plate style. 1-inch bayonets, clearance-holes 1 1/16 inches. Graded ports.

After the test the contacts were found to be slightly burned, and a slight carbon deposit was found on the quencher tubes. A test of the oil showed no visible trace of carbon.

O—Open. CO—Close-open.

† Larger values of short-circuit current were not imposed because of excessive arc lengths.

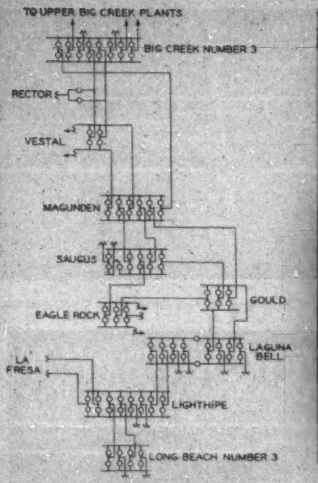

Figure 8. 220-kv system of the Southern California Edison Company, Ltd.

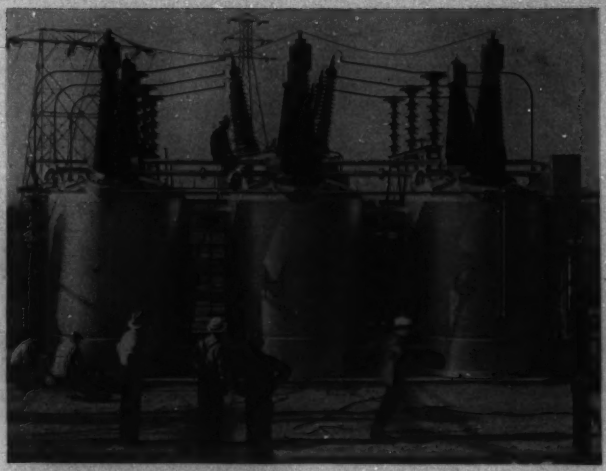

Figure 9. Kelman 230-kv 1,200-ampere 2,500,000-kva oil circuit breaker equipped with dethermalizer

arcs until the circuit is interrupted. At the time of extinction, fresh oil is between the contacts so no restriking occurs. In this arc quencher fourteen ports are used. The tube type operates in the same manner.

Further development has been made on a two-break device which will be the subject of a future paper.

Saugus and Laguna Bell Substations—Field Tests

In order to check the operation of these dethermalizers, actual phase-to-ground short-circuit tests were made on the main 220-kv system at the Saugus and Laguna Bell substations of the Southern California Edison Company Ltd. Figure 8 shows the 220-kv connections of the Edison system at the time of these tests.

The various kilovolt-ampere duties for the switch under tests were obtained by system arrangements. The lowest duty at these two locations was accomplished by feeding 220 kv to 66 kv and then back to 220 kv. This gave the impedance of the two transformer banks in series for limiting the short-circuit kilovolt-amperes. The other steps were accomplished by separating a line from a distant station, which supplied the test breaker. Then by selecting a shorter line the kilovolt-amperes duty was increased, and the final test at the two stations was the maximum kilovolt-amperes that could be delivered at the 220-kv bus, that is, all lines and transformer banks in service. At the Saugus substation this amounted to an equivalent three-phase short circuit of 1,730,000 kva, and at Laguna Bell it amounted to 2,259,000 kva.

The breakers at both locations performed perfectly throughout the tests without any mechanical trouble or without disturbing the system. After the series of tests the oil was tested and filtered and did not show any perceptible increase of carbon in the oil.

Figure 9 shows the test breaker at Laguna Bell substation. Figure 10 illustrates bars of various lengths that were placed on end on a steel plate between two tanks of the breaker. The mechanical movement of the breaker under test was so small that none of these bars were knocked over.

Table I is the tabulation of the tests taken at Saugus substation on October 4, 1936.

Table II is the tabulation of the tests taken at Laguna Bell substation on July 10, 1938 and July 31, 1938.

In these tests the type *C* dethermalizers are of the tube type, as shown by Figure 5, the *H* type are as shown by Figure 7, and the *A* type are of the flat-plate construction with more restricted ports.

The series of tests on July 10, 1938 were not continued above the values

Figure 10. Rods for determination of switch movement

The four steel pins were set on end to test for any jar to the breaker during opening of short circuits. Pins were turned square on ends and set on a 1-inch by 4-inch steel bar. On 230-kv tests at capacities from 554,000 kva to 2,259,000 kva, throughout a total of 16 tests, none of the pins fell. On the lighter tests, a high-speed moving-picture camera showed slight vibration of the pins, which vibration became less as the duty increased. On the heaviest tests, no vibration was found

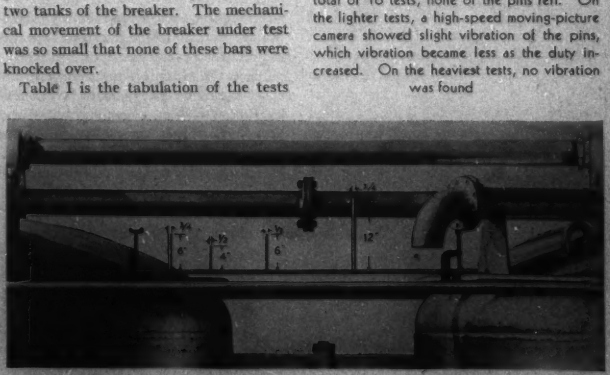

Figure 11 (above). Oscillogram of opening test at 2,259,000 kva

Figure 12 (below). Oscillogram of close–open test at 2,100,000 kva

shown because of the excessive arc length. It was discovered that these dethermalizers had too much clearance around the contacts and the ports were too much restricted, causing the oil to be forced out around the contacts giving practically no quenching effect. This difficulty was remedied, and the tests were completed on July 31, 1938.

It will be noted from these tables that as the duty increased the contact separation decreased at the time of arc extinction.

Oscillograph records were taken of these tests to give an accurate picture of the operation of the breaker. Figure 11 is an oscillogram of an opening operation with a full capacity short circuit at Laguna Bell substation. With the travel recorder it is possible to picture accurately the breaker action. From Figure 11 it can be seen that the arc was extinguished at exactly $^{3}/_{4}$-inch contact separation without any restrikes. Figure 12 is an oscillogram of a close–open operation of a full capacity short circuit at Laguna Bell substation. It can be readily seen from this figure that the prestrike was only $^{1}/_{4}$ inch, and contact separation at arc extinction was $^{7}/_{8}$ inch.

From these oscillograms and tables it should be noticed that dead time of the breaker was excessive. This was later corrected by a change in the tripping toggle.

It can be seen from the two oscillograms that no voltage disturbance occurred at arc extinction.

Since the Saugus tests were the first short-circuit tests to be made on the 220-kv Edison system, every precaution was taken to see that the 220-kv protection was in order and all switching was correct. The dispatching and switching were so well planned and the breaker functioned so perfectly that every test was carried out at the scheduled time without any system disturbance. This successful achievement allowed the privilege of future 220-kv short-circuit tests.

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A New One-Cycle Directional Overcurrent Relay

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Synopsis: This paper describes a new one-cycle directional overcurrent relay which is not limited in its application by lack of contact co-ordination. That contact co-ordination is important is indicated by the many incorrect relay operations which have been traced to the common practice of adding instantaneous attachment to directional overcurrent relays. For years it has been known that directional control is not sufficient for instantaneous directional overcurrent relays. This paper describes a new application of "memory action" which for the first time complements directional control to give always correct operation. The new idea is to use "memory action" to obtain a time delay in the operation of the overcurrent unit in the order of one-half cycle. Of course "memory action" is also used in the directional element to retain a high torque level even if the fault causes drastic voltage reduction. Both elements are of the rugged induction cylinder.

HIGH-speed relaying has become one of the most common means of permitting operation of a power system nearer its stability limit. Thus, extension of power transmission facilities has often been obviated. This, together with reduction of damage at the point of fault, has undeniably meant the saving of a large amount of critical material.

An important development in the high-speed relay family has been the distance relay with a stepped time–distance characteristic. With this type of relay, simultaneous instantaneous tripping is obtained for faults in the middle 80 per cent of the line section, and instantaneous tripping at one end for faults in the remaining 20 per cent. This is true over a large range of generating capacity.

For the protection of most of the lower voltage lines, distance relaying has generally been considered to be too expensive. On the other hand, it often occurs that the short-circuit currents of such lines are relatively fixed because the determining impedances are largely in the lines and transformers rather than in the connected generators. Thus, it is often possible to approach distance relay performance by means of instantaneous overcurrent relays. Generally, tripping must be allowed for faults in one direction only, thus necessitating directional action.

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Application Requirements

Any directional overcurrent relay, whether instantaneous or time delay, may operate incorrectly while the fault is being cleared or after it has been cleared, if the overcurrent unit is not prevented from

Figure 1. Basic system requiring correct directional action after fault is cleared

Figure 2. Basic system requiring correct directional action during sequence of circuit-breaker operation

closing its contacts when the fault is in the nontripping direction. Fundamentally, the cause of incorrect operation is the loss of a contact race. If the overcurrent unit has operated because of a fault in the nontripping direction, it must open its contacts before the contacts of the directional unit can close, under any condition causing reversal of the directional unit.

Figure 1 shows a system where the directional overcurrent relay at A might trip the circuit breaker at A incorrectly after the fault is cleared, if the overcurrent unit is allowed to operate during the fault. If the normal load current is as shown by the arrow, and a fault appears at X as indicated in Figure 1, the contacts of the directional unit open, and the contacts of the overcurrent unit close. The instant that circuit breaker B opens, the current through the relay at A reverses and drops in magnitude. The directional unit closes its contacts quickly because it now has full voltage and load current applied to it. The overcurrent unit, on the other hand, opens its contacts slowly if the magnitude of the load current is near the drop-out value of the overcurrent unit. If the directional-unit contacts close before the overcurrent contacts can open, circuit breaker A will be tripped falsely even though circuit breaker B has already cleared the fault.

Figure 2 shows a system where a directional overcurrent relay might operate incorrectly during the sequence of circuit breaker operations to clear the fault, because of the fault current reversing when the first circuit breaker opens. For example, when the fault occurs, the overcurrent and directional units at 4 operate. If the generation at A is greater than that at B, the overcurrent unit at 2 may also operate, but circuit breaker 2 is not tripped because the fault current is in the direction to hold the directional-relay contacts open. When circuit breaker 4 opens, the current through circuit breaker 2 reverses causing its directional relay to reverse. If the directional-unit contacts close before the overcurrent-unit contacts can open, circuit breaker 2 is falsely tripped.

For simplicity, parallel lines were used in Figure 2. The same difficulty may arise in loop circuits.

Instantaneous directional overcurrent relays for phase protection have a contact

Figure 3. High-speed directional overcurrent relay

race which is not present either in time-delay directional overcurrent relays or in instantaneous directional overcurrent relays for ground-fault protection. This is the race between the contacts of the directional-unit opening and the overcurrent contacts closing at the inception of the fault. For example, if load in Figure 1 is flowing in the direction of the arrow, the directional-unit contacts at A are closed. When the fault appears at X, the instantaneous overcurrent-unit contacts of the same relay begin to close. At the same time, the directional unit is attempting to open its contacts because of the reversal of the direction of current flow. Obviously, if the contacts of both units are closed simultaneously during the transition, circuit breaker A is tripped falsely.

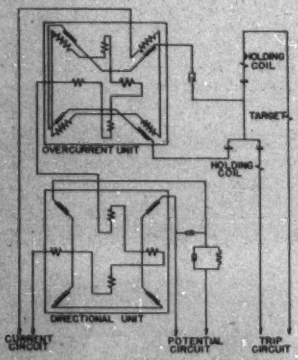

Figure 4. Internal connections of relay

Figure 5. Test oscillogram. Fault in non-tripping direction

Vibrator 1—Current in flux-shifting coils of overcurrent unit

Vibrator 2—Line current

Vibrator 3—Current in potential coil of directional unit

Vibrator 4—Voltage across potential circuit of directional unit

Vibrator 5—Current in trip circuit

Development of the Relay

In developing a high-speed directional overcurrent relay that operates correctly under any circuit condition, it is necessary to obtain proper contact co-ordination.

Directional control, as in the case of the time overcurrent relay, prevents incorrect tripping either after the fault is cleared or when there is a reversal of short-circuit current during the fault.

To win the more difficult contact race, namely, that occurring when a reverse current fault supplants load current in the tripping direction, it is necessary that the time required for the directional-unit contacts to open be less than the time for the overcurrent-unit contacts to close. This requirement suggests either that the directional unit should be fast even at very low voltage, or that the overcurrent unit should be delayed slightly. Actually, in order to increase the safety factor, both methods are employed. The overcurrent unit is delayed slightly by preventing the immediate rise of torque to its steady-state value. The operating time of the directional relay is decreased, principally at low voltage, by delaying the decay of current in the potential coil, retaining, at the same time, substantially, circuit frequency.

Description of the Relay

The relay consists of an overcurrent unit and a directional unit mounted in a single case. Figure 3 shows the relay, and Figure 4 shows the internal connections. In Figure 3, the upper unit is the overcurrent unit, and the lower unit is the directional unit. Both units are of the eight-pole induction-cylinder construction previously described.[1]

The main windings of the overcurrent unit consist of eight series-connected current coils.

As with all induction devices, the development of torque is dependent upon the difference in time phase between two or more fluxes. (This is not a complete explanation of the torque development of induction devices but is sufficiently explicit for present purposes.) Consequently, four of the current poles, in alternate position, have auxiliary coils. These windings provide a means of controlling or shifting the time phase of the air-gap flux of these poles. The four auxiliary coils, in series, are connected in series with a capacitor and one set of contacts of the directional unit. The torque of the overcurrent unit is proportional to the product of the square of the current and the sine of the angle between the fluxes produced in the shifted and unshifted poles. As long as the contacts of the directional unit are open, the fluxes in all poles are in phase and the torque of the overcurrent unit is zero. When the contacts of the directional unit close, the auxiliary coil circuit of the overcurrent unit is completed. This auxiliary circuit then shifts the phase angle of the flux in the corresponding poles so that it is no longer in phase with the flux in the other poles and the overcurrent unit has a torque in the direction to close its contacts.

The auxiliary circuit is an oscillating circuit, and the build-up of its current is delayed.[2] Since current in the auxiliary winding shifts the flux, a delay of the build-up of this current delays the flux shift. The build-up of current in the auxiliary winding is shown by the trace made by vibrator 1 of the oscillogram shown in Figure 6. This slow build-up

Figure 6. Test oscillogram. Fault in tripping direction

Vibrator 1—Current in flux-shifting coils of overcurrent unit

Vibrator 2—Line current

Vibrator 3—Current in potential coil of directional unit

Vibrator 4—Voltage across potential circuit of directional unit

Vibrator 5—Current in trip circuit

prevents the overcurrent unit from closing its contacts before the directional unit has time to open its contacts.

When the magnitude of the load current is near the pickup value of the overcurrent unit, the impulse that the overcurrent unit receives, under short-circuit conditions, before the contacts of the directional unit can open, will be sufficient to close the contacts of the overcurrent unit. The time required to close the contacts under this condition is greater than the time required to open the contacts of the directional unit, so that the trip circuit is not completed. This has been demonstrated by tests.

The windings of the directional unit consist of four current coils in series and four potential coils in series, mounted on alternate poles. The potential circuit has two capacitors and a resistor in addition to the coils. This potential circuit is also an oscillating circuit so that the flux in the potential coil does not immediately drop when the fault appears. The flux continues to follow system frequency for about one cycle which gives the directional unit ample torque to open its contacts quickly. This slow decay of the potential flux also gives the directional unit enough torque to close its contacts when the fault is in the trip direction even though the voltage across the potential circuit drops to a small value during the fault.

Figure 5 shows an oscillogram taken under the following conditions: Before the fault was applied, the directional relay had full potential. The current was in the direction to close the contacts of the directional unit but below the pickup value of the overcurrent unit. The instant the fault was applied, the current reversed and increased in magnitude to 13 times the pickup value of the overcurrent unit. Concurrently, the voltage across the potential circuit decreased to one per cent of rated potential. Vibrator 3 (Figure 5) shows how the current in the potential coils of the directional unit decayed. Vibrator 1 shows how the current in the auxiliary circuit of the overcurrent unit started to build up but was interrupted by the opening of the contact of the directional unit.

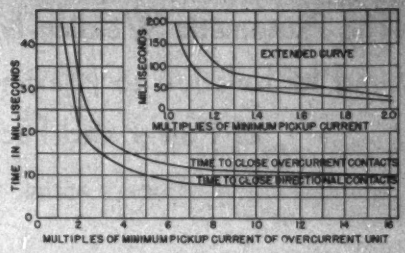

Figure 7. Time-current characteristic

Figure 6 shows an oscillogram in which the conditions were the same as those described heretofore except that the current before the fault was in the nontripping direction and in the trip direction after the fault. This oscillogram shows the build-up of the current of the auxiliary circuit after the directional unit closed (vibrator 1). The oscillogram shows that the contacts of the directional unit closed to complete the auxiliary circuit in approximately one-half cycle (60-cycle basis). Then the overcurrent unit operated to close its contacts in approximately one-half cycle. The trip circuit is therefore completed in approximately one cycle. Since this relay is capable of operating in one cycle, it is believed that it can be called instantaneous, notwithstanding the AIEE definition of "instantaneous," which is "no intentional time delay."

Relay Characteristics

The directional unit of the relay has maximum torque when the relay current leads the relay voltage by 45 degrees. This means that, with the quadrature connection, the relay has maximum torque when the relay current lags the phase-to-neutral voltage of the same phase by 45 degrees. The directional unit will operate correctly at the maximum torque angle with one per cent of rated voltage and the minimum pickup value at which the overcurrent unit can be set.

The time to complete the trip circuit depends upon the direction of the load current before the fault appears. If the load current is in the trip direction, the contacts of the directional unit will be closed and the time to complete the trip circuit is the time to close the contacts of the overcurrent unit. If the load current is in the nontripping direction before the fault, the contacts of the directional unit will be open, and the time required to complete the trip circuit will be the time to close the contacts of the directional unit plus the time to close the contacts of the overcurrent unit. Figure 7 shows the time to close the contacts of the overcurrent unit at various multiples of minimum pickup current. Figure 7 also shows the time to close the contacts of the directional unit when the potential circuit voltage drops to one per cent of rated voltage and the current increases to various multiples of minimum pickup current of the overcurrent unit.

Summary

The relay will operate correctly on parallel lines or on a loop circuit, regardless of whether or not there is a possibility of a reversal of current during a fault or immediately following the interruption of the fault.

The directional unit will operate correctly and quickly when a fault appears even if the potential circuit voltage drops to as low as one per cent of rated voltage.

The overcurrent unit will operate only when the contacts of the directional unit are closed.

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1. A Single-Element Polyphase Directional Relay, A. J. McConnell. AIEE Transactions, volume 56, 1937, January section, pages 77–80.

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The Automatic Welding-Machine Starter and Its Relation to Maximum Utilization of Power and Facilities

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ASSOCIATE AIEE

MANY electric-arc-welding applications are of such a nature that the welding machine is running with no load for a large percentage of the operating time. With this low utilization factor or "arc time," no-load power consumption becomes an appreciable item. In plants employing many machines there will be long leads between the machines and the work, either by necessity or for convenience. Under these conditions, the practicability of expecting the operator, or welder, to turn his machine on and off each time he plans to weld is certainly very remote. The automatic welding-machine starter has been developed to shut down the machine during the normal no-load running periods. Automatic starters have been in operation under average shipyard welding conditions for the past few months. Application of the automatic starters effects a very appreciable saving in power cost, about 25 per cent or more. In addition, a marked reduction in average demand on distribution systems is realized so that additional machines, up to 75 per cent, may be added without further power facilities expenditure.

The Apparatus and Its Operation

The automatic welding-machine starter is an electrical relay-control mechanism which may be connected to nearly any conventional single-operator a-c to d-c motor generator welding set. Operation of the unit is simple. When ready to strike an arc, the welder firmly touches his electrode, or rod, to the article to be welded, or work, and the welding machine starts. The machine continues to run as long as welding is in progress. When welding is finished, and after a predetermined delay period of no-load operation, the machine automatically stops. The cycle may then be repeated as often as is desired.

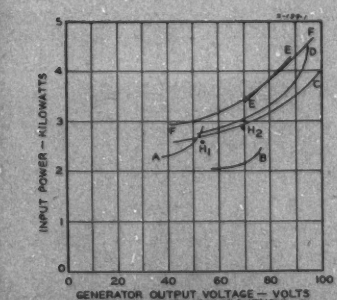

Figure 1. Welding-machine input power at no load

There are many methods of accomplishing the desired result from an electrical control standpoint. The apparatus must include the necessary relay and control components so that, when the electrode is touched to the work piece, that is, return or ground lead, thereby effecting an electrical contact, the machine will start and lock into the running position by the conventional line starter. Of particular interest is the time-delay relay as the no-load delay period directly effects power saving. A two- to three-minute interval is recommended to allow time for the welding machine to cool by ventilation. Moreover, according to welders themselves, two minutes should be allowed for changing rods and cleaning slag from the weld puddle. This prevents an unnecessary stop. Very short delay periods, such as one half a minute, increase the number of starts to a point where wear and tear on contacts is excessive. The automatic starter must be capable of immediately restarting, even at the instant the time-delay unit has called for stopping the welding machine. Any appreciable delay or erratic operation assignable to the electrical operation of the unit will have a detrimental psychological effect on the welder.

The numerous problems encountered in the development of a practical starter are mentioned but not analyzed here. Adaptability of the unit to various types and makes of welding machines, impedance of welding cable on steel plate, various contact resistances, the standstill impedance of welding generators,* and the requirements of various relays and component parts are matters of interest to the designer. A paper discussing these problems with circuit data will be prepared in the near future.

Relation to Power Cost

The no-load input for a group of popular welding machines is given in Figure 1. Nominal ratings are up to 400 amperes. Figure 2 is a plot of no-load power factor readings for the same group. The variation in input and power factor with output setting is expected and is a function of output voltage. Curves *C* and *D* represent machines with a wide range of open-circuit voltage. Less variation would be expected with machines of the more or less constant open-circuit voltage type, see curves *B* and *H*.

Power saving through the application of automatic starters is effected by many variables: the type of machine, type of welding,** output setting of the machine, the time-delay relay setting, and the cost of power.

Various power-saving tests were conducted. In all cases arc time was recorded. Arc time was measured with a synchronous time meter and relay control so that time was counted only when the arc was on. Power was measured with a graphic wattmeter for individual runs and by a watt-hour meter for banks of units. Graphic records provide other valuable data, such as the number of starts, duration of weld runs and off periods, and increase in power consumption with changes in output setting.

For arc times up to 35 per cent, the cumulative time of shutdown was found to vary between 6 and 14 hours on a 24-hour-day basis. The average centered about ten hours. The actual working-day period was checked from time-meter readings on welding machines without starters. This was found to be approxi-

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* The standstill impedance is the impedance measured across welding generator output terminals with generator at standstill.

** Power saving is effected by the type of welding that is, intermittency of welding, arc time, duration of weld runs, necessity for long delays because of fit-up, tacking, and so forth.

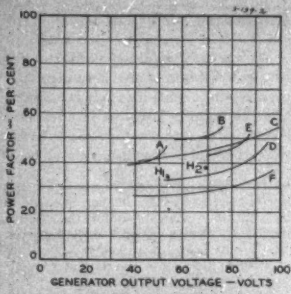

Figure 2. Welding-machine power-factor characteristics at no load

Table I. Power-Consumption Test

Test Number	1	2	3	4	5	6	7	8
Automatic starter connected during test	Yes	No	Yes	No	Yes	No	Yes	No
Test time (hours)	24	24	24	24	24	24	24	24
Power consumed by* four welding machines during test (kilowatt-hours)	277.7	284.1	199.1	378.1	305.0	462.3	315.0	497.5
Total number of arc hours of welding by four machines (hours)	20.99	15.66	19.8	23.96	26.53	26.29	23.8	27.0
Input per arc hour of welding (kilowatt-hours)	13.24	18.14	10.05	15.8	11.5	17.55	13.2	18.5
Average arc time, based on 21-hour work day (per cent)	25	18.6	23.6	28.5	30.4	31.3	28.4	32.1

Average values:
- Arc time ..... 27.3 per cent
- Kilowatt-hours per arc hour *without* starters 17.6
- Kilowatt-hours per arc hour *with* starters 13.0
- Saving in power with starters ..... 31.7 per cent
- Saving in power (kilowatt-hours per 24 hours per machine) ..... 31.8 kilowatt-hours

* Average no-load input 3 kw, average load input 12 kw.

mately 21 hours. The departure from a 24-hour day is accountable to shift-change and noon-hour periods. The product of the no-load losses, shutdown time, and power cost will yield dollar value of the power saving.

Actual test data of a bank of welding machines with and without starters are given in Table I. The criterion for comparison is arc time.† Power readings were taken using a three-phase watt-hour meter.

Statistics and Average Power Input

Experience and logic tell us that a power circuit supplying an intermittent load will handle a much higher connected horsepower than the same circuit under continuous operating connected load. Welding machines present a highly intermittent load.

Applying the statistical theory of sampling, we can show that, with a circuit of four welding machines operating on 25 per cent average arc time, the probability is 0.42 that we will find three machines at no load and one machine welding, the probability is 0.315 that we will find all four machines at no load, and the probability is 0.265 that there will be more than one machine welding.

It must be assumed that load conditions on the four welding machines, at any interval, represent a sample taken from a grand lot of weld (load) and no-weld (no-load) intervals,* the average arc time of which is known to be 25 per cent. Since each welder operates individually and without regard to what the others are doing, there is some justification in assuming a normal distribution of the weld and no-weld intervals. The binomial law is then applied using the formula:

$$P = \frac{n!}{(n-c)!c!} P^{n-c} Q^c$$

This is simply the probability of finding c defectives in a sample of size n, where n is the number of welding machines, c is the number not welding, P is the fraction effective or average arc time (25 per cent effective in grand lot), and $Q = 1 - P$ the average not welding or fraction defective (the average not welding in the grand lot of weld and no-weld intervals).

If we increase the sample size,** n, or number of welding machines, it can be seen that factorial calculations become laborious. Moreover, if we wish to calculate the probability that there will be not more than a given number of machines welding, it is necessary to sum up a group of terms. Calculations then make use of the incomplete beta function for which charts have been prepared.[1]

Using charts on the incomplete beta function, we can show that for 100 welding machines operating on a 25 per cent average arc time, the probability is 0.955 (extremely probable) that there will never be more than 36 machines welding. Likewise, we can show that the probability is 0.900 (highly probable) that there will be not more than 30 machines welding for a given interval. This may be expressed differently, that is, for at least 90 per cent of the time there will not be more than 30 machines welding and not less than 70 machines at no load.

The statistical analysis is interesting and gives us a fair approximation of how close we may load a distribution system to the average load limit. As the number of machines is increased, the statistical analysis is more accurate, and average load values may more safely be used.

Relation to Maximum Utilization of Facilities

The relation of automatic starters to maximum utilization of facilities can best be emphasized through a hypothetical example, making use of certain reasonable assumptions. Consider a distribution system operating at capacity and supplying 100 welding machines at an average arc time of 25 per cent.‡ Average no-load input is three kilowatts and 40 per cent power factor. (See Figures 1 and 2.) From test data, the average welding input is 12 kw and 85 per cent power factor. If no automatic starters are employed, the average input will be:

0.25×100×12 kw = 300 kw at 85 per cent power factor, 187 rkva, 355 kva
0.75×100×3 kw = 225 kw at 40 per cent power factor, 516 rkva, 562 kva
Average input = 525 kw, 877 kva, and 50.8 per cent power factor.

If the machines are operated on a 21-hour work-day period and the installation of automatic starters results with an average shutdown time of ten hours per day per machine. Converting hours to per cent time on a 25 per cent arc time basis, the average input will be:

0.25×100×12 kw = 300.0 kw at 85 per cent power factor, 187 rkva, 355 kva
0.274×100×3 kw = 82.2 kw at 40 per cent power factor, 188 rkva, 205 kva

Average input is 382.2 kw, 535 kva, and 71.5 per cent power factor. The application of starters effects a decrease 27.2 per

† For shipyards, 25 per cent arc time is believed to be a conservative average.

* From graphic instrument charts and impulse counter readings, it is found that the number of impulses, or times that a welding arc is struck, in a 24-hour work day will be in order of 2,000. This may substantiate the concept of weld and no-weld intervals and accordingly, statistical normality.

** It is sometimes convenient to calculate factorial n when n is not too large. Stirling's formula gives satisfactory results. The formula:

$$n = n^n e^{-n} \sqrt{2\pi n}$$

For $n = 10$, the error is only 0.8 per cent.[1]

‡ The machines were welding, on the average, for 25 per cent of the time, or 5.25 hours on a 21-hour-work-day basis. They were off, on the average of ten hours, and running at no load on the time-delay relay period for the balance of the time, 5.75 hours, which is 27.4 per cent of the period.

Table II

Item	Method 1 Additional Capacity	Method 2 Power-factor Correction	Method 3 Starters
1. Facilities cost	$ 7,900.00 (a)	$ 8,730.00 (b)	$ 9,600.00 (c)
2. Power cost, per month for 160 machines	3,933.00	3,601.00	2,775.00
3. Original power cost per month for 100 machines	2,460.00	2,460.00	2,460.00
4. Additional power cost per month for operating 60 machines (item 2 minus 3)	1,473.00	1,141.00	315.00
5. Additional power cost for 6 months period	8,850.00	6,846.00	1,890.00
6. Cost of facilities and power for 6 months (item 1 plus 5)	16,750.00	15,576.00	11,490.00
7. Cost per machine per month for 6 months period (not including machine cost)	279.00	260.00	191.00
8. Per cent of unit machine cost @ $450.00 per unit	62 per cent	27.7 per cent	42.5 per cent
9. Continued power saving per month over method 1	None	332.00	1,158.00

(a). 550 kva of additional capacity at $15.00 per kilovolt-ampere installed.

(b). 873 kva of correction required at $10.00 per kilovolt-ampere installed.

(c). 160 starters at $60.00 each installed. No allowance is made for maintenance in method 3. This item must ever be recognised where moving parts, that is, relays, and so forth, are employed. It is believed, however, that the maintenance cost for starters would be at least offset by the decreased maintenance cost on the welding machines themselves, because, on account of the starters, their total running time will be greatly reduced.

cent in average kilowatt demand, 39 per cent in average kilovolt-ampere demand, 46.7 per cent in average reactive-kilovolt-ampere demand, and an increase of 11.7 per cent in average power factor. With power at $0.01 per kilowatt-hour, on a 21-hour work-day period, this amounts to approximately $900 per month. If the installed cost is $60.00 per unit, starters will pay for themselves on power savings alone in less than seven months. The average reactive demand is reduced by 328 reactive kilovolt-amperes. In equivalent capacitance correction, at $10.00 per kilovolt-ampere installed, this represents more than half the first cost of the starters.

In the example, application of automatic starters allows for an increase of 64 per cent in capacity or 64 additional welding machines on the already loaded distribution system. Higher arc times will increase the average input and reduce the additional capacity allowance, and vice versa. Power saving and investment value will depend upon power rates and schedules. The saving will increase where power is sold on some form of kilovolt-ampere-hour basis.

Suppose in this hypothetical case, it was decided to purchase 60 additional welding machines at a cost of $450.00 each. Since the distribution system is operating at capacity, power supply for the new machines becomes a serious problem. There are three solutions to the problem:

1. Installation of additional distribution capacity.

2. Power factor correction of the existing system.

3. Application of automatic welding machine starters.

It may be desirable to write off the expenditure in a short period such as six months.

Using a typical rate, power cost is $0.007 per kilowatt-hour, and the total charge per month is decreased or increased, respectively, by 0.25 per cent for each one per cent average power factor above or below 85 per cent. Estimates, neglecting interest, depreciation, and items common to all methods, are given in Table II.

A continued power saving of $332.00 per month by method 2 and $1,158.00 per month by method 3, over method 1, will be realized. Longer investment periods will naturally place the balance more and more in favor of the automatic welding-machine starters. It is believed that the figures used and shorter period are in keeping with many wartime expansion policies. It is of interest to note that a combination of capacitance correction and starters would allow for more than doubling the capacity of the original loaded system in the example.

Conclusions

The automatic welding-machine starter has been in operation under average shipyard welding conditions for a sufficient length of time to prove its practicability and merits. Application of automatic starters offers two principal advantages:

1. A very recognizable saving in power cost is effected because the welding machine is automatically shut down for the greater part of its normal no-load operating time. Test results show this saving to be in order of 25 to 30 per cent of the total power consumed for average arc times of 25 per cent and with a three-minute delay setting on the automatic starter. The saving will vary with different welding application and will increase as the average arc time is reduced and with shorter time-delay relay settings. Since the no-load input for a-c to d-c motor–generator welding sets is inherently of a low power factor nature, application of automatic starters greatly reduces the average reactive-kilovolt-ampere demand (in the order of 50 per cent reduction), so that the average kilovolt-ampere input is reduced far more than the average kilowatt input. The economic advantage of automatic starters on a purely power cost saving analysis is entirely dependent upon power rate schedules and will be more favorable where power is sold on some form of kilovolt-ampere-hour basis.

2. Probably the most important advantage offered by the application of automatic starters is that, by reducing the average kilowatt and kilovolt-ampere demand, appreciable increase in capacity on existing distribution systems may be realized. The increased capacity allowance will vary from 25 per cent to 75 per cent, depending upon arc time and other conditions, and may be over 100 per cent in cases where starters are used in combination with capacitance correction.

It is believed that the application of starters will warrant consideration where new or additional distribution facilities are contemplated. In general, starters will show a greater economic advantage over any other method of reducing overall power and facilities cost and, in any case, will provide for the maximum utilization of welding power distribution systems.

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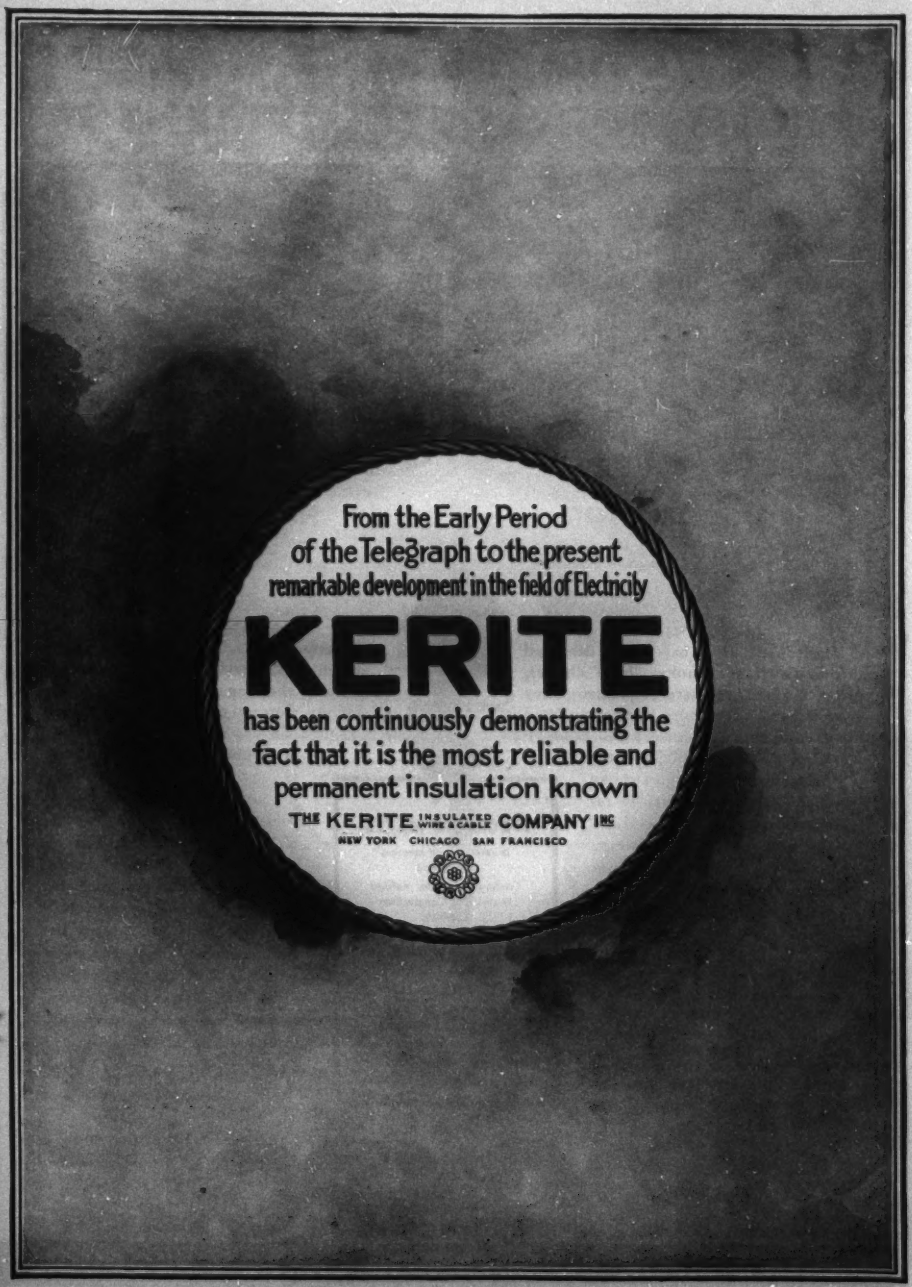
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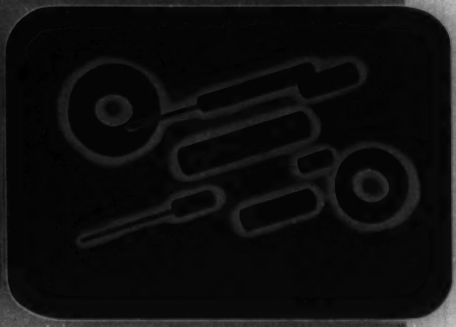

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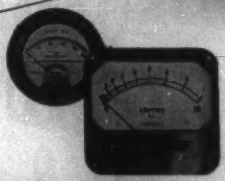

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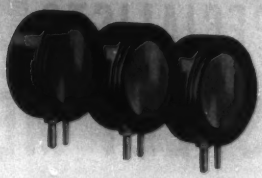

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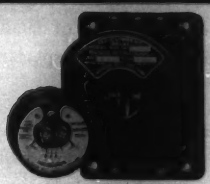

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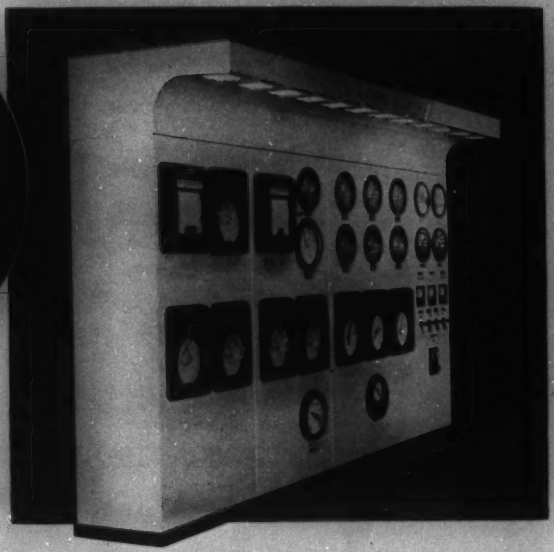

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Vacuum Tubes and Amplifiers. Vacuum Tube Design: (Nomenclature, Coefficients, Terminology, Formulas, Electrode, Dissipation Data, Filament Characteristics.) Ultra-High Frequency Tubes, Vacuum Tube Amplifier Design: (Classification, General Design, Graphical Methods.) Resistance Coupled Audio Amplifier Design, Negative Feedback, Distortion, Army and Navy Preferred List of Vacuum Tubes, Cathode Ray Tubes, Approximate Formulas.

Telephone Transmission. Power Ratio, Voltage Ratio, Decibel Table, Transmission Line Data and Constants.

Radio Frequency Transmission Lines. Transmission Line Data: (Surge Impedance of Uniform Lines, Transmission Line Types and Their Characteristic Impedance, Impedance Matching with Shorted Stub, Impedance Matching with Open Stub.) Wave Guides and Resonators.

Radio Propagation and Antennas. Field Strength of Radiation from an Antenna, Field Strength from an Elementary Dipole, Ultra-Short Wave Propagation: (Line of Sight Transmission Distance.) Reflection Coefficient of Plane Radio Waves from Surface of the Sea, Distance Ranges of Radio Waves, Radio Transmission and the Ionosphere, Time Interval between Transmission and Reception of Reflected Signal, Linear Radiators: (Maxima and Minima of Radiation—Single-Wire Radiator.) Antenna Arrays: (Radiation Pattern of Several Common Types of Antennas, Radiation Pattern of Multi-Element Linear Broadside Array, Radiation Pattern of Multi-Element Binomial Broadside Array.) Frequency Tolerances.

Noise and Noise Measurement. Wire Telephony, Radio.

Non-Sinusoidal Waveforms. Relaxation Oscillators, Electronic Differentiation Methods, Fourier Analysis of Recurrent Waveforms, Analyses of Commonly Encountered Waveforms.

Dimensional Expressions.

Greek Alphabet.

Mathematical Formulas and General Information. Miscellaneous Data, Mensuration Formulas, Formulas for Complex Quantities, Algebraic and Trigonometric Formulas, Approximations for Small Angles, Quadratic Equation, Arithmetical Progression, Geometrical Progression, Combinations and Permutations, Binomial Theorem, Maclaurin's Theorem, Trigonometric Solution of Triangles, Complex Hyperbolic and other Functions, Great Circle Calculations.

Mathematical Tables. Logarithms of Numbers and Proportional Parts, Natural Trigonometric Functions for Decimal Fractions of a Degree, Logarithms of Trigonometric Functions for Decimal Fractions of a Degree, exponentials (e^{n} and e^{-n}), Natural or Naperian Logarithms, Hyperbolic Sines, Hyperbolic Cosines, Hyperbolic Tangents, Bessel Functions.

USE THIS CONVENIENT ORDER FORM

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Federal Telephone and Radio Corporation
67 Broad Street, New York 4, N. Y.

I enclose .....dollars for which send me..... copies of *"Reference Data for Radio Engineers"* ($1.00 per copy)

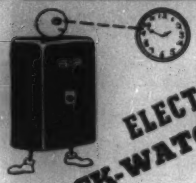
Name .....

ELECTRICAL ENGINEERING

Address .....

City ..... State .....

HELP WANTED? *Try electronic production aids*



ELECTRONIC CLOCK-WATCHER

Why pay men to watch a clock? G-E electronic timers handle precise timing operations, release workers for more useful work elsewhere in the plant. Five ranges to choose from—between 1/20 second and two minutes. Special ranges on request. Consistent. Stepless time range controlled by knob on front. Only one moving part. Only one tube. Can be used to time injection-molding machines, induction furnaces, conveyors, photographic exposures, laboratory operations, and for many other purposes. Thousands in use. 110 or 220 volts, a-c. Price, $28 and up. Write, stating your timing problem.

PHOTOELECTRIC RELAYS IN STOCK!

Limited quantity of high-speed relays (CR7505N100). More than 450 operations a minute. Operate on light-intensity change of ½ foot-candle. Time delay up to ½ second for holding relay closed after light impulse, which may be as short as 0.001 second. Excellent for simple register-control jobs. Automatic seal-in circuit if desired. Relay contacts handle up to 10 amp at 230 volts. Operate on 115 or 230 volts, a-c, 50/60 cycles. Power consumption, 30 watts. Many special features.

ARE YOU MAKING MOTORS?

OR TRANSFORMERS? **Now you can test winding insulation right on the production line. New G-E electronic winding-insulation tester simulates severest operating stresses and tests turn-to-turn, coil-to-coil, and coil-to-ground insulation. Reveals shorted turns, wrong number of turns, or incorrect connections. Complete test takes only a few seconds on production line and may save your customers hours of repair work later. Operates on 115-volts, single phase, 60-cycles. Write for more information.**

LESS MAINTENANCE on Resistance Welders

—by replacing mechanical contactors with G-E ignitron contactors. No moving parts! No contactor tips to dress. No noise. No open arc. No time lag. Faster production. More exact timing. These electronic contactors use long-life G-E ignitron tubes. One installation paid for itself in four months. More information in Bulletin GEA-3058B.

SIMPLIFY ADJUSTABLE-SPEED DRIVE ELECTRONICALLY

New G-E Thy-mo-trol drive gives you full, stepless speed control on a single dial. Operates from a-c power. No gears, clutches, or belts needed to vary speed. Smooth, shockless acceleration at maximum permissible rate. No current peaks on line. Dynamic braking for quick stops. Holds speed within plus or minus 2 per cent, from no load to full load under full field. Maximum torque at low speeds! It pulls and pulls and pulls. Compact. Easy to install. Motor is the only major moving part. Ask about CR7507. Now supplied in sizes from ¼ to 15 hp. Special forms and ratings if you need them.

DO YOUR WORKMEN SQUINT

—WHEN DAYLIGHT DIMS? ***G-E electronic light control turns on lights whenever daylight level is too low—turns them off when daylight is sufficient. Saves eyes, helps maintain production, saves power. Low cost. Bulletin GEA-2679B gives installation information, diagrams.***

READY-MADE SKILLS FOR NEW WORKERS

Electronic apparatus for timing, sorting, counting, and controlling is making many wartime jobs easier to learn and easier to do. For example, one manufacturer found that the training period for new riveters was shortened considerably, and results were improved, by using electronic timers to automatically time the riveting hammers. Electronics may be the answer to a similar training problem in your plant. *General Electric Company, Industrial Control Division, Schenectady, N. Y.*

The best investment in the world is in this country's future—BUY WAR BONDS

GENERAL ELECTRIC

General Electric, Sec. A676-109
Schenectady, N. Y.

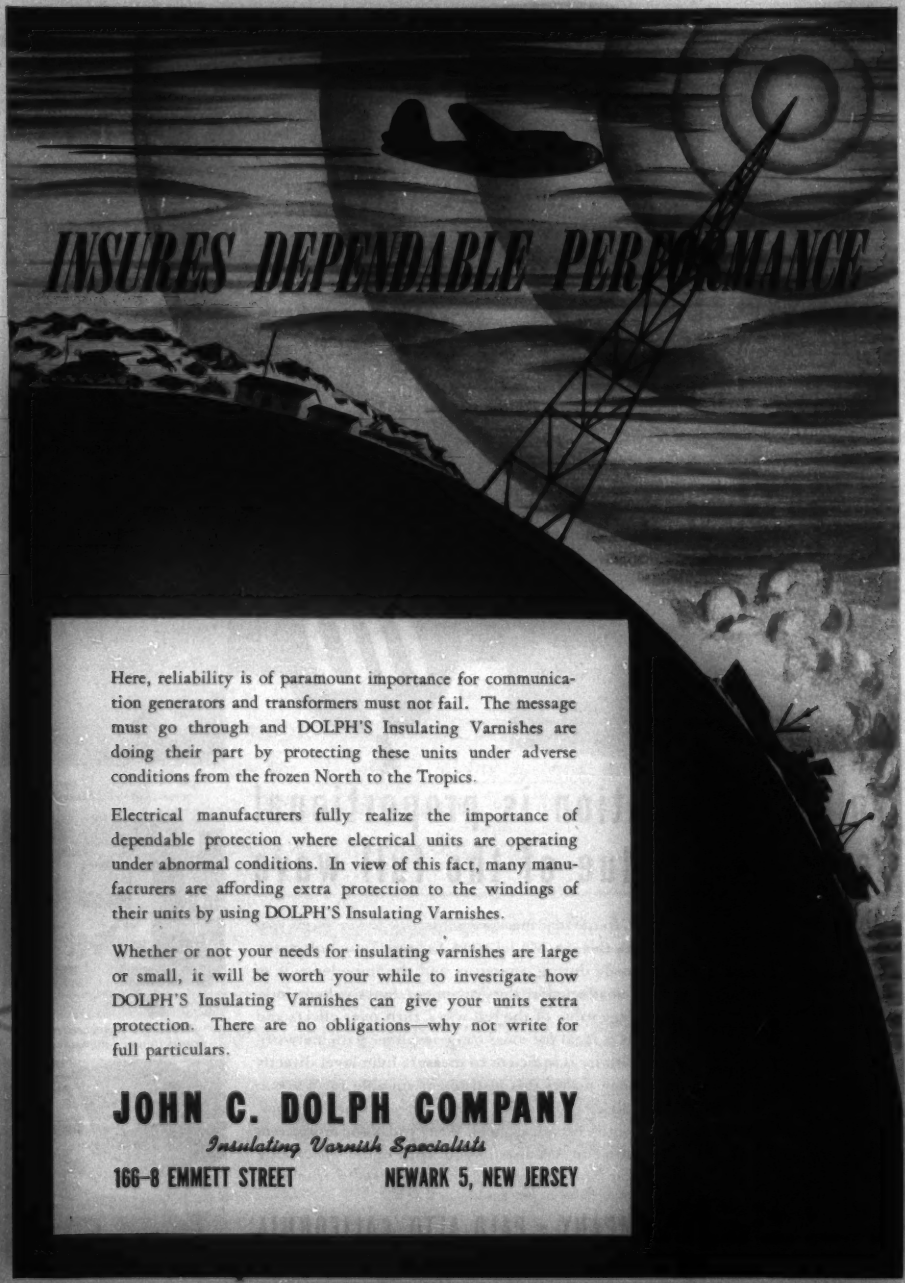
Please send me the bulletins checked:

- ☐ Photoelectric relays, GEA-1755E
- ☐ Electronic contactors for resistance welders, GEA-3058B
- ☐ Automatic light control, GEA-2679B
- ☐ Thy-mo-trol drive
- ☐ Electronic timers
- ☐ Winding-insulation tester

Name .....

Company .....

Address .....



Here, reliability is of paramount importance for communication generators and transformers must not fail. The message must go through and DOLPH'S Insulating Varnishes are doing their part by protecting these units under adverse conditions from the frozen North to the Tropics.

Electrical manufacturers fully realize the importance of dependable protection where electrical units are operating under abnormal conditions. In view of this fact, many manufacturers are affording extra protection to the windings of their units by using DOLPH'S Insulating Varnishes.

Whether or not your needs for insulating varnishes are large or small, it will be worth your while to investigate how DOLPH'S Insulating Varnishes can give your units extra protection. There are no obligations—why not write for full particulars.

JOHN C. DOLPH COMPANY

Insulating Varnish Specialists

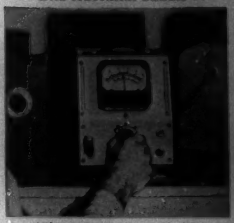
166-8 EMMETT STREET NEWARK 5, NEW JERSEY

Meter has two scales providing voltage and DB calibrations

Light in weight and equipped with convenient handle

Voltage indication is proportional to average value of the full wave

YOU CAN MAKE accurate high frequency measurements *(up to one megacycle)* without particular precautions with this *-hp-* Model 400A Vacuum Tube Voltmeter. There are no adjustments to be made during operation and the impedence is so high the circuit being measured is unaffected by the instrument. Since voltage indication is proportional to the average value of the full wave, turn-over effects and waveform errors are minimized. It is ideal for measuring amplifier gain, network response and output level. Its sensitivity is sufficient to measure hum level directly in many cases. Wide frequency range makes this instrument suitable for work at audio frequencies from 10 cps to 20 kc and also for carrier current work in supersonic region, in television and the entire broadcast field. Write today for more complete data on this outstanding instrument. Ask also for your copy of the *-hp-* catalog ...24 pages of technical information plus complete listing of all *-hp-* instruments.



The 400A is unexcelled for production or laboratory work

HEWLETT-PACKARD COMPANY • PALO ALTO, CALIFORNIA

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CRESFLEX NON-METALLIC SHEATHED CABLE • SERVICE ENTRANCE CABLE • MAGNET WIRE • BARE WIRE

CRESCENT
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Wire

Under latest government regulations, no crude rubber is used in the manufacture of these wires, yet through the substitution of plentiful Buna S Synthetic Rubber they retain the inherently superior moisture-resistant, long-life properties of rubber insulation. They carry Underwriters' Laboratory labels, and are approved under the National Electric Code for *all interior wiring systems*, and are the most available wires in wholesalers hands at present and for the duration.

WAR PRODUCTION 100%

"CRESFLEX"
Non-metallic
Sheathed Cable

CRESCENT INSULATED WIRE & CABLE CO.

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WIRE and CABLE
Factory: TRENTON, N. J.—*Stocks in Principal Cities*

CRESCENT ENDURITE SUPER-AGING INSULATION • WEATHER-PROOF WIRE

θ...*little known enemy of fighter planes*

As ELECTRICAL ENGINEERS know, the Greek letter theta, θ, often stands for relative humidity.

Whenever θ is high, it's bad news for the electrical wiring and cable on fighter planes. For moisture in the air could so foul up the electrical system that it could prevent a quick take-off from an advanced camouflaged base like that pictured in the illustration.

The untiring efforts of the electrical industry, however, have licked this moisture problem.

Electrical design engineers put many kinds of materials and impregnants to exhaustive tests in their search for the proper insulation with high moisture resistance.

And they hit the right combination in the newest, most improved impregnants and Fiberglas.*

Because the individual fibers in Fiberglas Electrical Insulations are all glass, they do not absorb moisture, are highly moisture-resistant. *In addition, they are highly resistant to heat . . . unaffected by most acids . . . possess high dielectric strength when combined with the proper impregnants.*

Miles and miles of power and lighting cable aboard many types of planes are Fiberglas-insulated. Approximately 85% of radio hookup wire for transmitters and receiving sets in aircraft is Fiberglas-insulated.

These facts are a measure of the successful use of Fiberglas by the electrical industry.

Besides, there are other huge and ever growing wartime demands for Fiberglas-insulated motors and generators in the Army and Navy Air Forces. Vast quantities of Fiberglas also go into other electrical equipment needed on warships and in the mechanized units of the Army.

Our production was tremendously increased this last year. Right now, it is constantly expanding month by month. YET—vital Army and Navy needs have so far kept pace with this expansion. These are the reasons why your electrical distributor has not always been able to fill orders promptly.

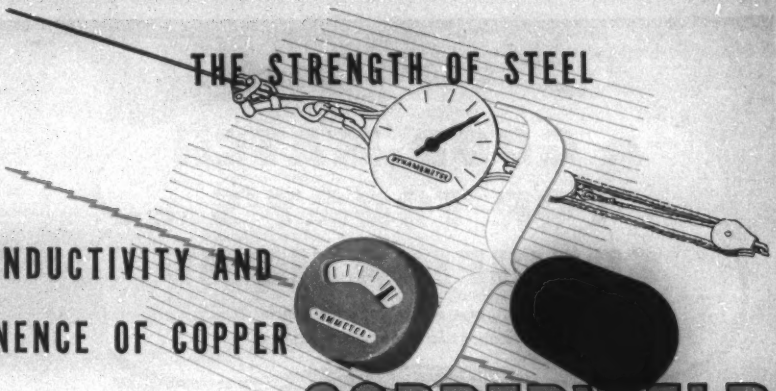
• • •

Owens-Corning Fiberglas Corporation, Toledo, Ohio. In Canada, Fiberglas Canada, Ltd., Oshawa, Ontario.

FIBERGLAS* ELECTRICAL INSULATIONS

*T. M. Reg. U. S. Pat. Off.

THE STRENGTH OF STEEL

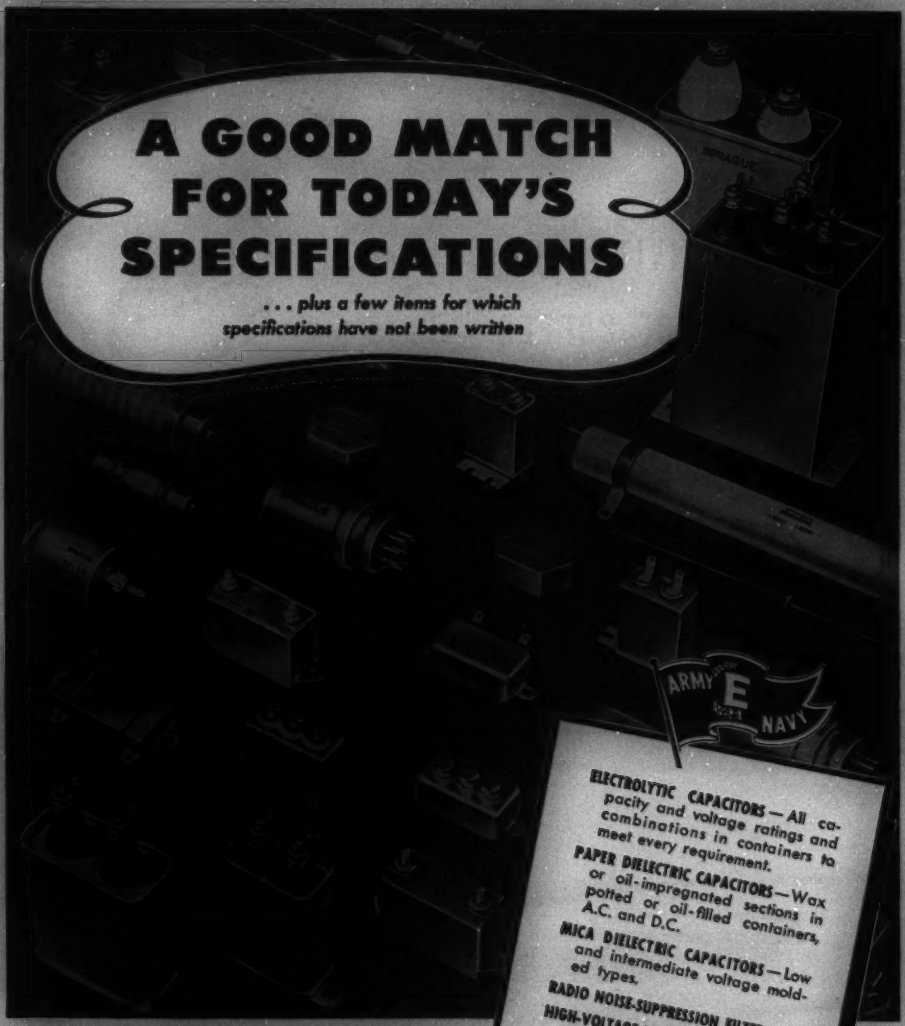


THE CONDUCTIVITY AND PERMANENCE OF COPPER

COPPERWELD

Copperweld wire derives its strength from its core of strong steel—steel permanently protected against rusting by a thick exterior of copper. The copper need only do the job that copper does best—provide *rust resistance and electrical conductivity*. The steel need only do the job that steel does best—*provide strength*. No other wire combines the strength of steel with the conductivity and permanence of copper.

Copperweld Steel Company GLASSPORT, PA.


A GOOD MATCH FOR TODAY'S SPECIFICATIONS
. . . plus a few items for which specifications have not been written
ARMY E NAVY
ELECTROLYTIC CAPACITORS—All capacity and voltage ratings and combinations in containers to meet every requirement.
PAPER DIELECTRIC CAPACITORS—Wax or oil-impregnated sections in potted or oil-filled containers, A.C. and D.C.
MICA DIELECTRIC CAPACITORS—Low and intermediate voltage molded types.
RADIO NOISE-SUPPRESSION FILTERS
HIGH-VOLTAGE NETWORKS
KOOLOHM RESISTORS—Wire-wound power types, hermetically-sealed power types, precision meter multipliers, bobbin-type resistors, etc.
SPRAGUE SPECIALTIES COMPANY
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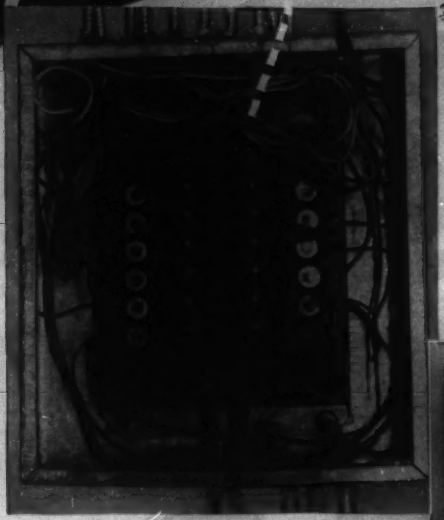
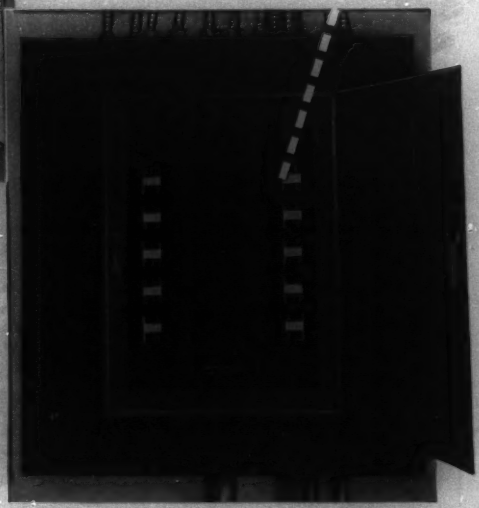
CAPACITORS
QUALITY COMPONENTS • EXPERTLY ENGINEERED • COMPETENTLY PRODUCED

Problem AND Solution



Problem: An obsolete and overloaded fusible type panel. It provided only 12 lighting and power circuits. More were needed.



Solution:
A new Square D Multi-breaker panelboard, installed in the old box, using the same conduit. Provides 20 circuits... 66⅔% more capacity.

Multi-breaker lighting and distribution panels, when installed in existing panel boxes, usually increase the number of circuits by more than 50%. They eliminate fuses completely... provide modern convenience and protection. There are literally hundreds of plants that can profit tremendously by such conversion... right now.

ELECTRICAL EQUIPMENT • KOLLSMAN AIRCRAFT INSTRUMENTS

SQUARE D COMPANY

DETROIT • MILWAUKEE • LOS ANGELES

HERE'S THE NEW AMPAC '400' TO SAVE YOU MONEY!

1 It's an *a-c* welder — with no arc blow! Capacity is 50 to 500 amps — *the* ideal size. Note how simple, rugged the new Ampac is...

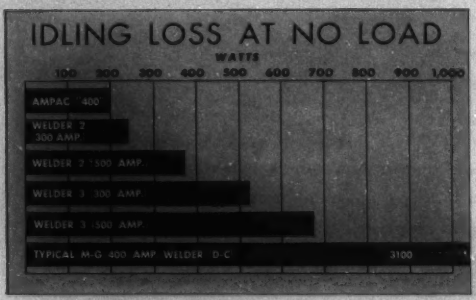
2 Here's power! Transformer coil has oversize rectangular winding—glass-insulated — with primary over secondary. Air duct prevents breakdown.

3 One inch movement of upper core — only 7 easy turns of wheel — covers entire welding range! Result: less wear, time saved!

4 Lower core is 1-piece, U-shaped, die-punched silicon steel. Eliminates air gaps, cuts idling loss. Note 1-piece welded frame, heavy angles.

5 Extra heavy welding terminal will stand years of abuse. All permanent connections are *brazed!*

6 Sturdy lifting frame bolts to *core* for direct lifting of heavy mechanism. No load on case. Damage to case can *not* affect structure of electrical parts.



7 Compare Ampac with the 2 largest selling a-c welders and a typical d-c welder. At 2¢ per kw/hr, the d-c unit wastes $1.49 in a full day; Ampac's loss is less than 10¢! *And* — Ampac is more *efficient* than these welders!

A 1665

IT WILL pay you to get the full story on these brilliant new Ampacs. A new, patented circuit increases efficiency, cuts operating costs. Available in 200 amp units and up. Write for bulletins B6241, B6302.

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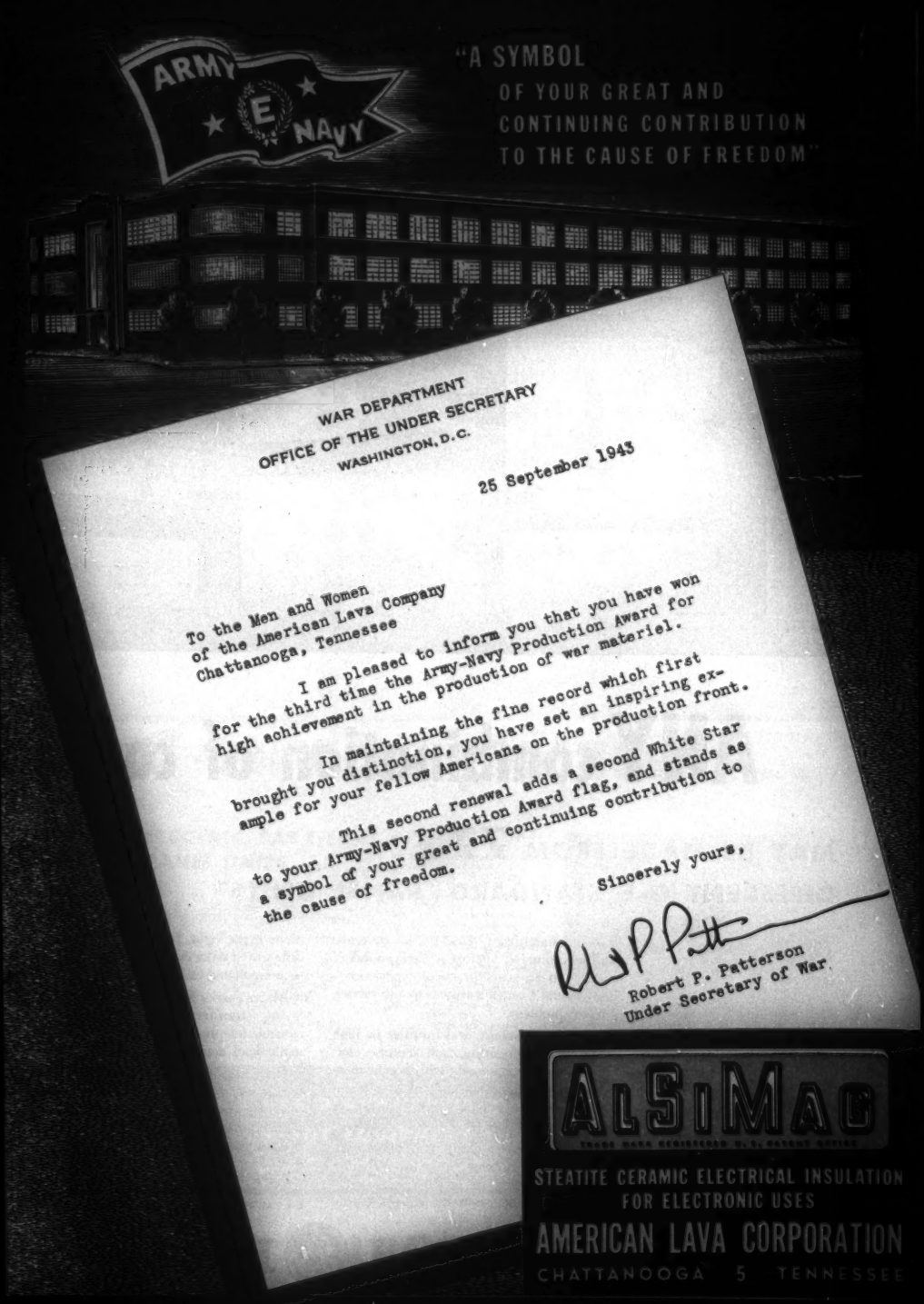
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NAVY
"A SYMBOL
OF YOUR GREAT AND
CONTINUING CONTRIBUTION
TO THE CAUSE OF FREEDOM"
WAR DEPARTMENT
OFFICE OF THE UNDER SECRETARY
WASHINGTON, D.C.
25 September 1943
To the Men and Women
of the American Lava Company
Chattanooga, Tennessee
I am pleased to inform you that you have won for the third time the Army-Navy Production Award for high achievement in the production of war materiel.
In maintaining the fine record which first brought you distinction, you have set an inspiring example for your fellow Americans on the production front.
This second renewal adds a second White Star to your Army-Navy Production Award flag, and stands as a symbol of your great and continuing contribution to the cause of freedom.
Sincerely yours,
Robert P. Patterson
Under Secretary of War
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STEATITE CERAMIC ELECTRICAL INSULATION
FOR ELECTRONIC USES
AMERICAN LAVA CORPORATION
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ANY combination of carrier

MAY BE MADE FROM 77 DIFFERENT G-E STANDARD "PANEL UNITS"

THESE standardized "panel units"—designed and co-ordinated against a background of more than 20 years' practical experience—are General Electric's answer to any carrier-current problem.

Compact, efficient, and uniform in high quality and engineering, each combines electrically and mechanically with one or more of the other 77 units—and with standard cabinets of convenient size for indoor or outdoor installation.

No other carrier equipment offers such flexibility in design or function. Whether your requirements are met by an assembly the size of a suitcase or the 24-unit equipment at the right, future needs for more or different carrier-current services will be accommodated easily and economically.

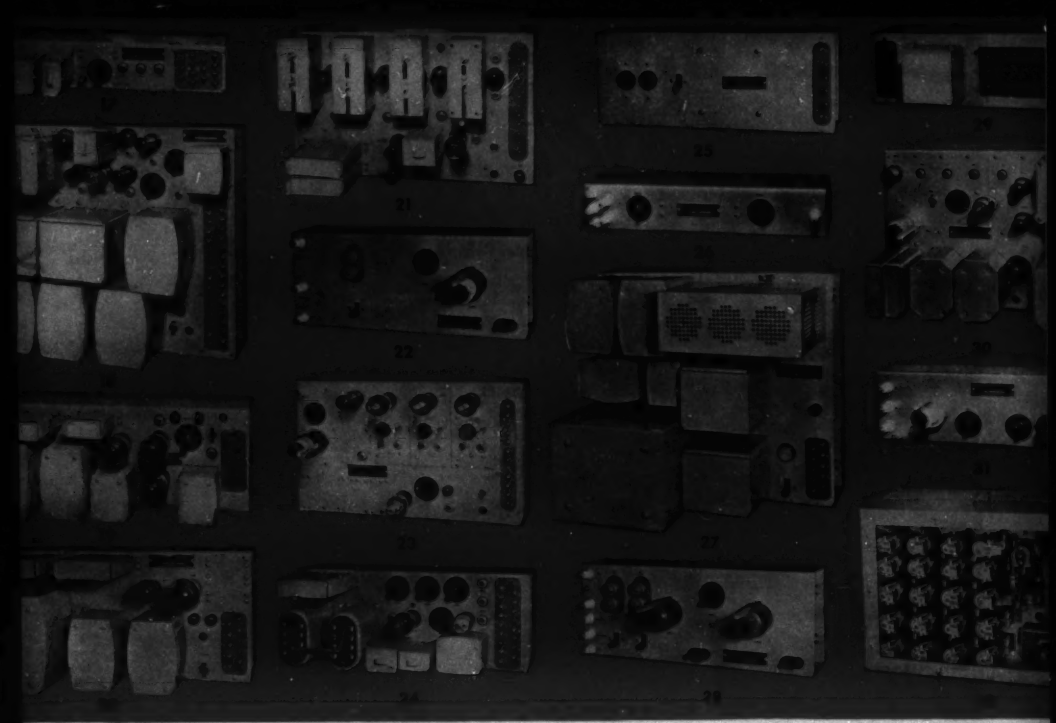
Major carrier functions include pilot relaying, transferred tripping, supervisory control, telephony, telemetering and automatic load control.

General Electric engineers will be glad to discuss your needs, and to help you select the most suitable combination. Write to *Electronics Department, General Electric, Schenectady, New York.*

• **Tune in "The World Today" every evening except Sunday at 6:45 E.W.T. over CBS. On Sunday listen to the G-E "All Girl Orchestra" at 10 P.M. E.W.T. over NBC.**

GENERAL ELECTRIC

181-BK-5950



current services you need . . .

GENERAL ELECTRIC CARRIER-CURRENT *PANEL UNITS*

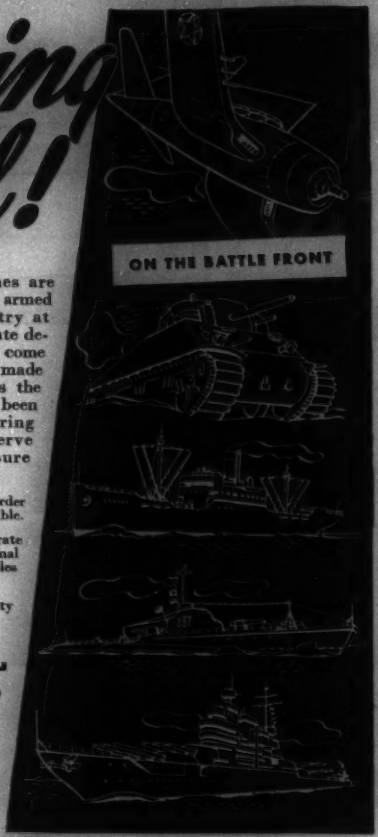
1. Carrier-frequency amplifier.
2. Fuse-alarm unit.
3. Telephone modulator.
4. Telemetering transmitter.
5. Meter unit.
6. Superheterodyne receiver.
7. Supervisory control transmitter.
8. Relaying modulator.
9. Simplex telephone auxiliary.
10. Transmitter, 50-150 kc.
11. Audio filter and relay.
12. Single-frequency duplex telephone control.
13. Audio oscillator.
14. Transmitter-modulator, 50-150 kc.
15. Two-frequency line tuning.
16. Simplex telephone auxiliary, 800-cycle, ringing.
17. Single-frequency duplex telephone code ring.
18. Power supply for selective ringing.
19. Audio amplifier.
20. Power supply for audio units.
21. Telemetering or control receiver.
22. Single-frequency ground-return line-tuning unit.
23. Load-control or supervisory transmitter.
24. Two-frequency duplex telephone control.
25. Input-voltage control.
26. Impedance matching transformer.
27. Power pack for carrier-frequency amplifier.
28. Interphase line-tuning unit.
29. Telephone-line protective-and-jack unit.
30. Telemetering or control transmitter.
31. Double trapping unit.
32. Selective ringing unit.

GENERAL ELECTRIC HAS PLANNED AND BUILT MORE CARRIER-CURRENT EQUIPMENT THAN ALL OTHER MANUFACTURERS COMBINED

CARRIER CURRENT

THE NERVE NETWORK OF THE POWER SYSTEM

Serving Well!



"NATIONAL" Brushes are serving well with our armed forces and with industry at home. While the immediate demands of the emergency come first, every effort is being made to give all our customers the service to which they have been accustomed. When ordering "National" brushes observe these precautions to insure prompt delivery.

1 Anticipate your needs and order as far in advance as possible.

2 Give complete and accurate information on your original purchase order. Include samples and drawings when necessary.

3 Secure best possible priority rating.

NATIONAL
TRADE-MARK
CARBON, GRAPHITE AND METAL-GRAPHITE BRUSHES

LET'S GO! U.S.A. KEEP 'EM FLYING!

CONSERVATION AND CARE WORK HAND IN HAND

In the present emergency it is particularly essential that your electrical equipment be kept running constantly and at full efficiency. Proper cleaning and elimination of minor faults will do much toward accomplishing this objective.

The Modern Pyramids Bulletins pictured above give practical suggestions on care and maintenance of brush-using electrical equipment. They are available to you without charge.

The word "National" and the three pyramids symbol are trade-marks of National Carbon Company, Inc.

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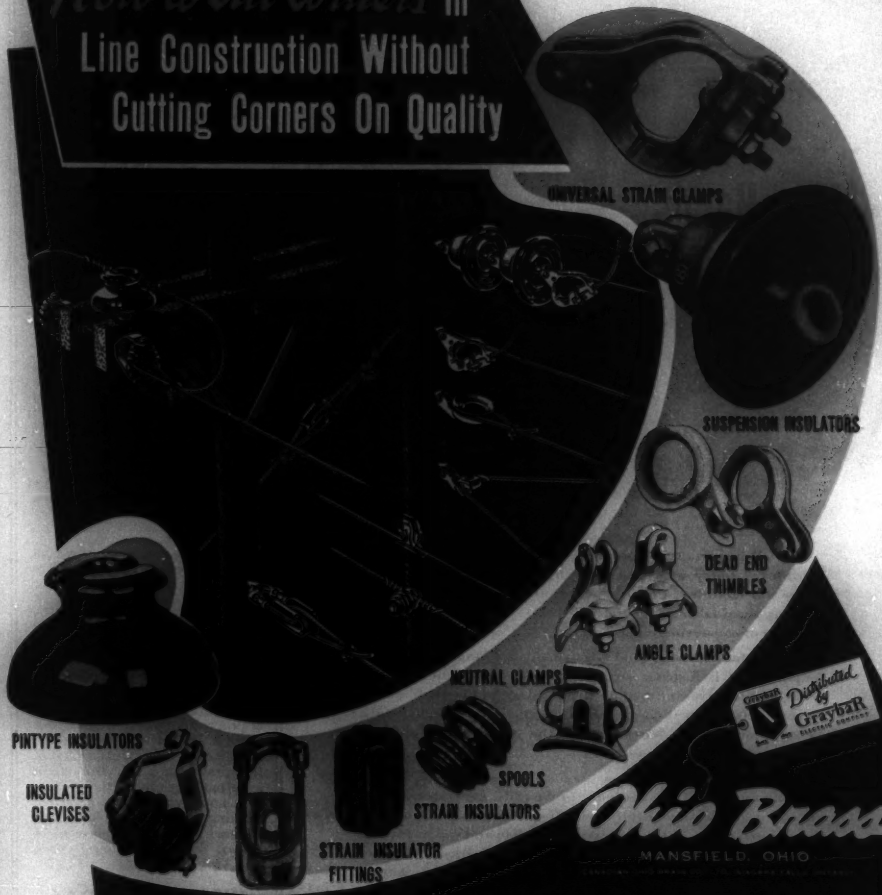
How to Cut Corners In Line Construction Without Cutting Corners On Quality



Distributed by Graybar

Ohio Brass

MANSFIELD, OHIO

There's a lot of information in this booklet and we'd like you to have it. It's a class of material distributed by Graybar from products of the Ohio Brass Company, one of the leaders in the electrical industry. Ingenious designs that save time and labor are based on long experience. Materials are the same as employed in the highest voltage applications. They add up to all-around satisfaction. And the difference between time-proven materials and unknown "bargains" is so slight that just one trouble call will wipe it out. You won't make that call when you build with O-B. Get these materials from Graybar—as handy as your 'phone.

8498-H

FOR VICTORY BUY UNITED STATES WAR BONDS AND STAMPS

More Hands Needed

Our all-important program of production for invasion is confronted today with a serious threat—manpower shortage. Many war factories in critical areas have exhausted their available supply of labor and are now directing their attention to the problem of conserving manpower.

Deltabeston Asbestos- and Glass-insulated Magnet Wires are helping war industries save many precious man-hours by reducing motor rewinding jobs to a minimum. Electrical maintenance crews are finding out that motors protected with Deltabeston Magnet Wires stay on the job longer in spite of continuous peak-load operations.

Deltabeston and Deltaglass Magnet Wires are designed for winding motors, lifting magnets, brake coils, generators, starters and other electrical equipment. They withstand high operating temperatures. Both are extremely flexible and can be formed into the most intricate coils. Deltabeston and Deltaglass Magnet Wires are available in round, square and rectangular shapes.

You can obtain additional information by requesting a Deltabeston Wire and Cable Catalog. It's yours for the asking. Write to Section Y1032-32, Appliance and Merchandise Dept., General Electric Company, Bridgeport, Conn. G-E Deltabeston Asbestos- and Glass-insulated Wires are distributed by Graybar Electric Co., G-E Supply Corp. and other G-E Merchandise Distributors.

GENERAL ELECTRIC

WANTED for the PHILCO ENGINEERING STAFF

- **RADIO—ELECTRONICS—ELECTRICAL ENGINEERS**
  Men with degrees in electrical engineering or comparable experience in radio and television.
- **MECHANICAL ENGINEERS**
  Men with college degrees or comparable experience in the engineering aspects of electrical appliances, and in designing small machinery.
- **DESIGN ENGINEERS — DRAFTSMEN**
  Men with experience in mechanical designing, especially of small metal parts and of the automatic machinery to mass-produce them.
- **PRODUCTION ENGINEERS**
  Including electrical and mechanical engineers familiar with any phase of radio, radio-phonograph and television production.
- **PHYSICISTS**
  Must have science degree in physics. Some practical experience in radio is desirable.

WE expect the men who qualify for these positions to become permanent members of our staff and take an important part in our post-war program.

To maintain the Philco tradition of progressive research and development, is first and foremost in our minds. We provide the finest of technical equipment. But often, even more helpful is the inspiration and personal assistance of working with men who have done so much for the advancement of Radio, Television, Refrigeration and Air-Conditioning.

WRITE US TODAY

Qualified men not now engaged in work requiring their full talents, are invited to write us in detail as to their experience, education, family and draft status, and salary. Letters will be treated in strict confidence.

Hiring subject to local W. M. C. rulings.

WRITE TO MR. GEORGE DALE

PHILCO CORPORATION
Philadelphia 34, Penna.

LET US SOLVE YOUR

BRAZING PROBLEMS

Whether you are interested in a

PORTABLE SELF-CONTAINED BRAZING UNIT

which requires only a power connection up to 75 KVA

Or in a small

5 KVA PORTABLE AIR-COOLED UNIT

or

A SMALL BENCH-TYPE BRAZING MACHINE

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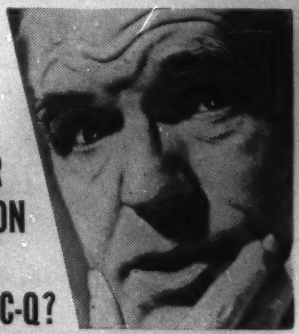

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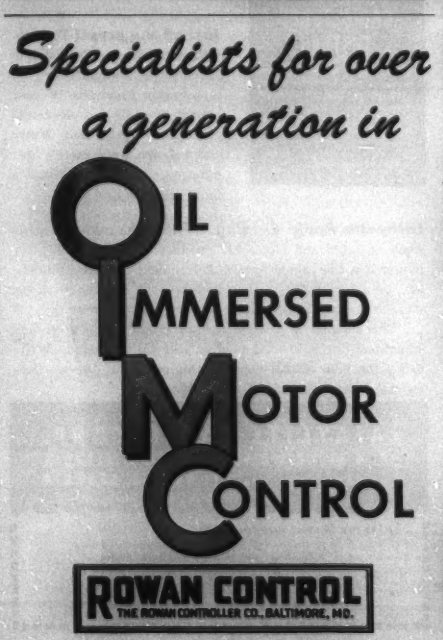
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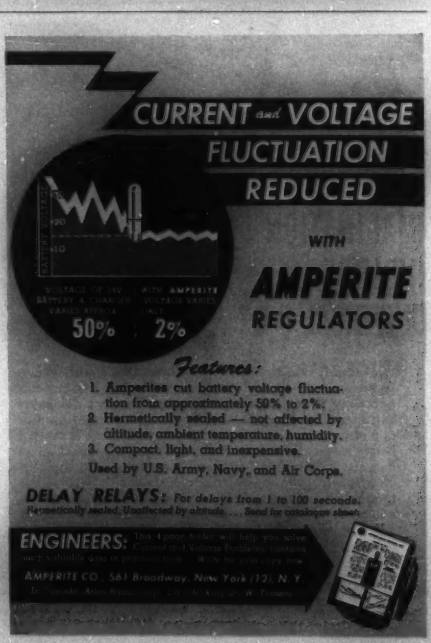
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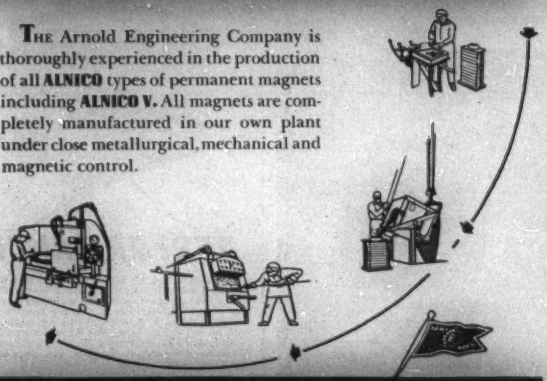

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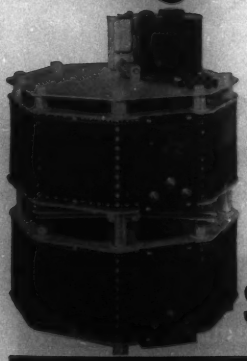

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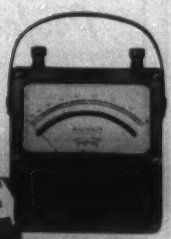

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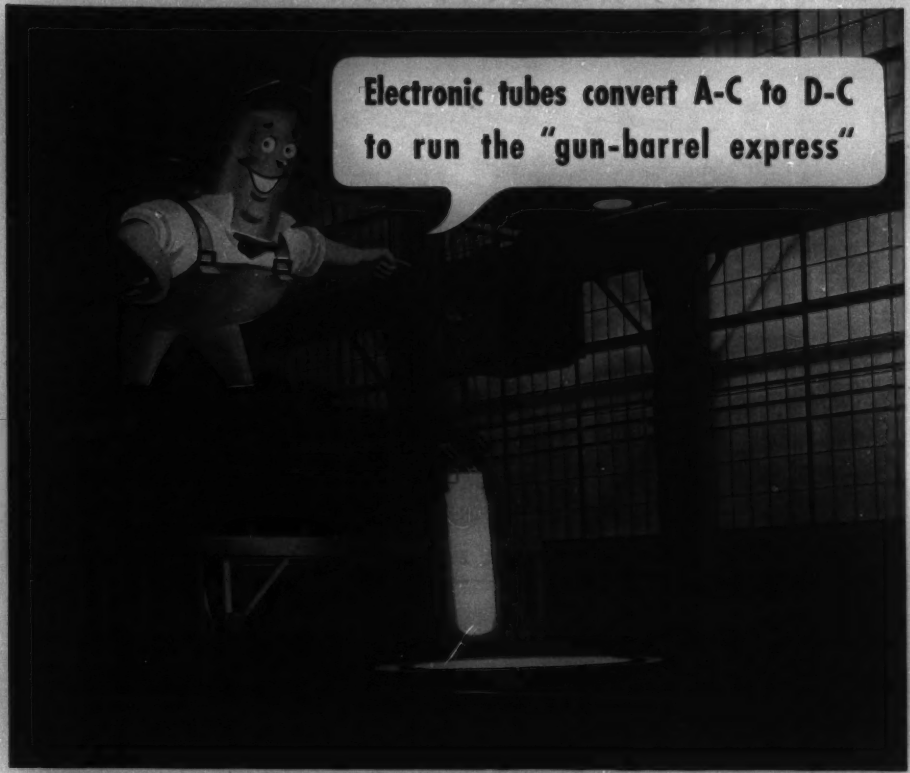

The General Electric sealed ignitron is used instead of rotating machinery

THIS traveling crane, 100 feet long, is suspended from the sides of a war plant turning out gun-barrels for destroyers. Its power supply offers an excellent example of electronic tube application.

Direct current is essential for precision crane operation. Here, rectifiers using the G-E steel-jacketed ignitron (available in ratings from 20 amp to 200 amp) provide D-C at about the same installed cost as rotating machinery, but at lower operating costs.

This electronic tube has no moving parts. It requires no special foundation. It is quiet in operation. Overall efficiency is high, and practically constant over the entire load range.

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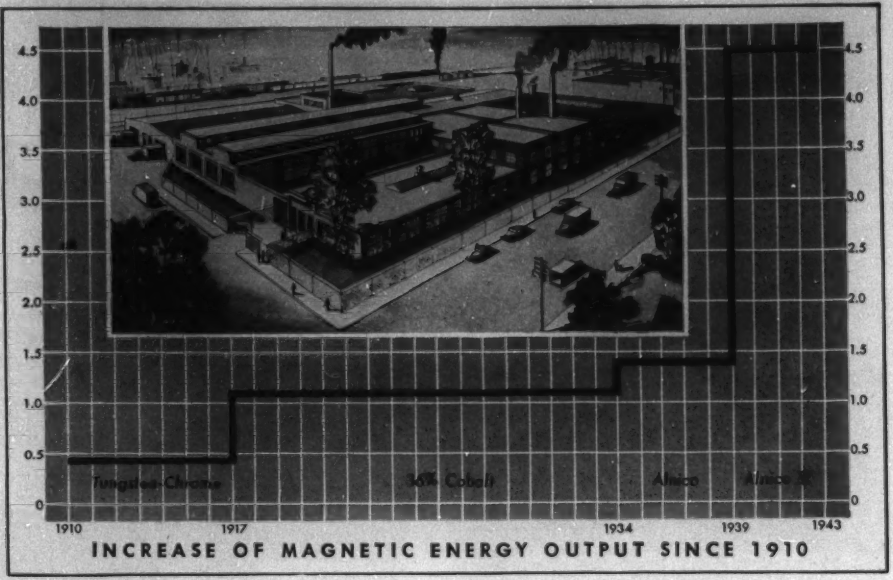

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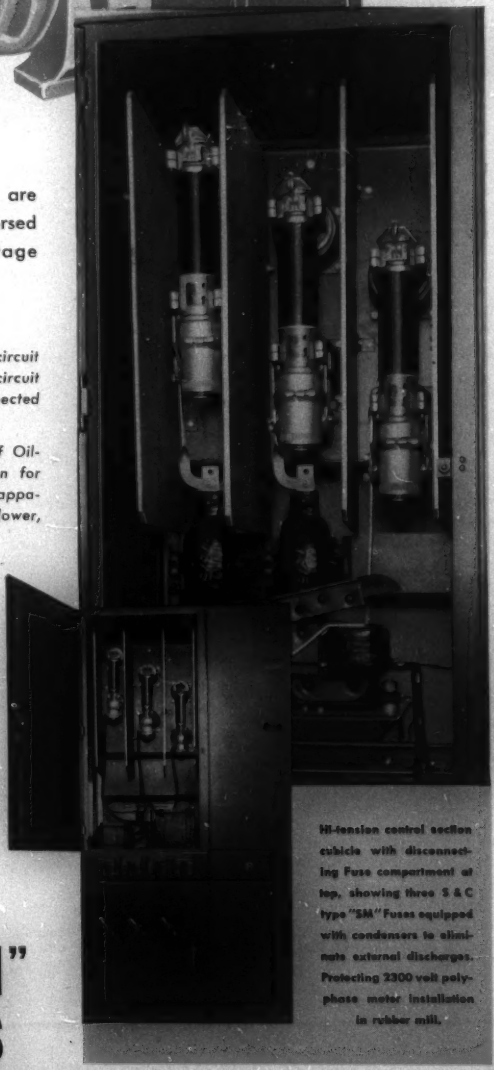

Hi-tension control section cubicle with disconnecting Fuse compartment at top, showing three S&C type "SM" Fuses equipped with condensers to eliminate external discharges. Protecting 2300 volt polyphase motor installation in rubber mill.

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Keeps a firm grip on popularity

because of its *firmer grip* on the conductors!

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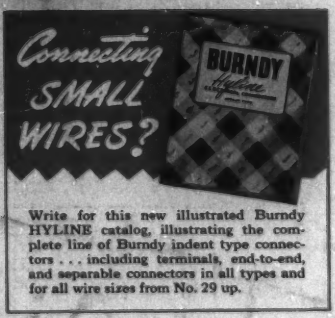

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